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MCNP/MCNPX Model of the Annular Core Research Reactor

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Abstract

Many experimenters at the Annular Core Research Reactor (ACRR) have a need to predict the neutron/gamma environment prior to testing. In some cases, the neutron/gamma environment is needed to understand the test results after the completion of an experiment. In an effort to satisfy the needs of experimenters, a model of the ACRR was developed for use with the Monte Carlo N-Particle transport codes MCNP [Br03] and MCNPX [Wa02]. The model contains adjustable safety, transient, and control rods, several of the available spectrum-modifying cavity inserts, and placeholders for experiment packages. The ACRR model was constructed such that experiment package models can be easily placed in the reactor after being developed as stand-alone units. An addition to the "standard" model allows the FREC-II cavity to be included in the calculations. This report presents the MCNP/MCNPX model of the ACRR. Comparisons are made between the model and the reactor for various configurations. Reactivity worth curves for the various reactor configurations are presented. Examples of reactivity worth calculations for a few experiment packages are presented along with the measured reactivity worth from the reactor test of the experiment packages. Finally, calculated neutron/gamma spectra are presented.

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NOMENCLATURE

ACPR	Annular Core Pulse Reactor
ACRR	Annular Core Research Reactor
ACRR-CC	Annular Core Research Reactor Central Cavity
ACRRF	Annular Core Research Reactor Facility
Al6061	Standard designation for a specific aluminum alloy
B_4C	Boron carbide
BeO	Beryllium oxide
C/E	Calculation-to-Experiment ratio
DC	Delayed Critical
FREC	Fuel-Ringed External Cavity (Two versions I and II)
HDPE	High-density polyethylene
ID	Inner Diameter
IP	Isotope Production
LP-1	Lead-polyethylene spectrum modifying bucket
MCNP	Monte Carlo N-Particle Transport Code
MCNPX	Monte Carlo N-Particle eXtended Transport Code
MJ	Mega-joules
NG	Neutron Generator
NuGET	Neutron Gamma Energy Transport Code
Pb-B_4C	Lead-boron spectrum modifying bucket
RES	Radiation Effects Sciences
RHP	Right Hexagonal Prism
RML	Radiation Metrology Laboratory
SAR	Safety Analysis Report
SNL	Sandia National Laboratories
SNLRML	Sandia National Laboratories-Radiation Metrology Laboratory
UO_2	Uranium oxide
U-ZrH	Uranium-zirconium hydride

EXECUTIVE SUMMARY

Experimenters at the ACRR have a need to predict the neutron/gamma environment prior to testing. In some cases, the neutron/gamma environment is needed to understand the test results after the completion of an experiment. The high neutron fluxes and gamma dose rates make a measurement of the gamma ray spectrum impossible with current technology. Calculated gamma spectra are used to determine the gamma ray environments for testing in the ACRR. An experiment plan must contain an estimate of the reactivity worth of the experiment package prior to gaining approval for reactor experiments on the test package. In an effort to satisfy the needs of experimenters, a model of the ACRR was developed for use with MCNP [Br03] or MCNPX [Wa02]. The model contains adjustable safety, transient, and control rods, several of the available spectrum-modifying cavity inserts, and placeholders for experiment packages. The ACRR model is constructed such that experiment package models can be easily placed in the reactor model after being developed as stand-alone units. An addition to the "standard" model allows the FREC-II cavity to be included in the calculations.

This report presents the MCNP model of the ACRR. In addition to a detailed description of the model, comparisons are made between the model and the reactor for various configurations. Calculated and measured reactivity worth curves for the control rod bank for the various reactor configurations are presented. Examples of reactivity worth calculations for a few experiment packages are presented along with the measured reactivity worth from the reactor test of the experiment packages. Finally, calculated neutron/gamma spectra are presented.

The integral reactivity worth curves (both measured and calculated) are fit to a functional form that corresponds to the results of perturbation theory. The total control rod bank worth differs by ~$1.08 between the MCNP model and the standard (pulse) configuration of the ACRR. However, the difference between the model and the measured worth curves is constant for control rod bank movements less than 2250 rod units. A linear fit to the difference for movements greater than 2250 rod units allows an adjustment in the estimates of experiment package reactivity worth.

The differential reactivity worth was estimated and compared to measurements for nine experiment packages. Three of the packages required movement of the control rod bank greater than 2250 rod units. The adjustment described above was applied to the estimated reactivity of those three packages. The average of the difference between the measurement and calculation for the nine unadjusted package reactivity worth estimates is -$0.153 +/- 0.239. The average of the absolute deviation for the unadjusted package reactivity worth estimates is $0.200 +/- 0.197. The average of the difference between the measurement and calculation for the adjusted package reactivity worth estimates is -$0.029 +/- 0.084. The average of the absolute deviation for the adjusted package reactivity worth estimates is $0.076 +/- 0.039. Although this series of comparisons shows excellent agreement, the results found here may not be typical. For experiment packages that are more complicated than these examples, the differences may be much greater than the ~$0.08 seen above in the adjusted reactivity worth estimates. A more realistic value for the total uncertainty associated with any particular reactivity worth estimate is +/-$0.50.

The neutron spectra for two different reactor environments (ACRR-Central Cavity and the Pb-B_4C spectrum-modifying bucket) were calculated and are compared to experimental neutron spectra determined by spectrum unfolding techniques using activation foils. The spectrum calculated for the ACRR-Central Cavity agrees quite well with the experimentally determined ACF9 spectrum. In fact, 85 out of the 89 neutron energy groups (~96%) are within 15% agreement. However, the thermal portion of the calculated Pb-B_4C spectrum-modifying bucket spectrum disagrees drastically with the experimentally determined TPB13 spectrum.

The photon spectra in various reactor environments at the ACRR are currently unable to be measured due to the high ionizing dose rates. These high gamma dose rates in the reactor are often the reason the ACRR is chosen for a given experiment. The MCNP model of the ACRR provides the best available estimates of the gamma spectra in the various environments. The gamma spectra for two different reactor environments (ACRR-Central Cavity and the Pb-B_4C spectrum-modifying bucket) were calculated and are displayed.

1. INTRODUCTION

The Annular Core Research Reactor (ACRR) is a water-moderated pool-type research reactor capable of pulse and steady-state operations. The reactor is fueled by a 236 element array of uranium dioxide/beryllium oxide (UO_2-BeO) clad with stainless steel. The fuel is uranium enriched to 35 weight percent ^{235}U, with 21.5 weight percent UO_2 and 78.5 weight percent BeO. The ACRR is controlled by two fuel-followed safety rods, three poison (void-followed) transient rods, and six fuel-followed control rods. The control elements (safety, transient, and control rods) make up part of the 236 elements for the normal core configuration.

The ACRR has a dry irradiation cavity, 23 cm in diameter, that occupies the center region of the core and extends past the surface of the pool. In addition to the central irradiation cavity, there is the capability of using large (38 and 51-cm diameter) fuel-ringed external cavities (FREC-I and FREC-II) for irradiations. The FREC cavities are fueled by uranium-zirconium hydride (U-ZrH) fuel elements (20 weight percent ^{235}U enrichment). These irradiation locations, along with spectrum-modifying cavity inserts [lead-boron (Pb-B_4C) and lead-polyethylene (LP-1)], provide the facility with the ability to change the inherent neutron spectrum found in the reactor as well as allowing adjustment of the neutron to gamma dose ratio. The ACRR is primarily used for testing electronics, materials, and fissile components. It has also been utilized in reactor safety experiments and medical isotope production.

Experimenters at the ACRR have a need to predict the neutron/gamma environment prior to testing. In some cases, the neutron/gamma environment is needed to understand the test results after the completion of an experiment. The high neutron fluxes and gamma dose rates make a measurement of the gamma-ray spectrum impossible with current technology. Calculated gamma spectra are used to determine the gamma-ray environments for testing in the ACRR. An experiment plan must contain an estimate of the reactivity worth of the experiment package prior to gaining approval for reactor experiments on the test package. In an effort to satisfy the needs of experimenters, a model of the ACRR was developed for use with MCNP [Br03] or MCNPX [Wa02]. (*NOTE: In this report, MCNP will be used generically for both computer codes.*) The model contains adjustable safety, transient, and control rods, several of the available spectrum-modifying cavity inserts, and placeholders for experiment packages. The ACRR model is constructed such that experiment package models can be easily placed in the reactor after being developed as stand-alone units. An addition to the "standard" model allows the FREC-II cavity to be included in the calculations.

This report presents a MCNP model of the ACRR. (*NOTE: Other models of the ACRR using MCNP surface descriptions (based on an original model by Wesley C. Fan of SNL) have been used for safety analysis report for the ACRR (ACRR SAR) [Na99] analyses and radiation environment calculations.*) In addition to a detailed description of the model, comparisons will be made between the model and the reactor for various configurations. Reactivity worth curves for the various reactor configurations will be presented. Examples of reactivity worth calculations for a few experiment packages will be presented along with the measured reactivity worth from the reactor test of the experiment packages. Finally, calculated neutron/gamma spectra will be presented. The neutron spectra will be compared to experimental neutron spectra determined by spectrum unfolding techniques using activation foils.

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2. ACRR MODEL DESCRIPTION

2.1. ACRR With FREC-II Decoupled

The MCNP model of the ACRR is constructed of several components. The components are the lattice elements, reactor core configuration loading, the central cavity, the central cavity additions, external features (e.g., grid plates and nickel plates), central cavity inserts (e.g., aluminum dosimetry bucket and Pb-B_4C bucket), and a section for placing experiment packages into the reactor model. The components in this portion of the model were created using the macrobody (combinatorial geometry) features of MCNP. In fact, only one cell has the historical MCNP surface description (All previous models of the ACRR used MCNP surface description).

The following "outline" describes how the ACRR model was created.

1. Lattice elements were constructed as "universes" in MCNP. The lattice elements are regular fuel elements, 90% fuel elements, fuel-followed control rods, fuel-followed safety rods, void-followed transient rods, nickel elements, aluminum (void) elements, and water elements. The control elements each have a transformation that allows that element to be moved to positions that correspond to experiment configurations.

2. Using the lattice elements, a fuel loading that reflects the core configuration of the ACRR as of May 2003 was produced.

3. The central cavity was modeled and placed in the proper location in the core configuration. The central cavity model has comments that describe how an analyst can change reactor configurations (e.g., add pedestals and/or central cavity inserts).

4. The central cavity additions (32" pedestal and 8" pedestal) were modeled. These cavity additions were modeled to be easily added or removed by changing comment cards.

5. The features external to the reactor core (top and bottom grid plates, the nickel plate and window to the neutron radiography tube, and the FREC side nickel plate) were modeled.

6. The central cavity inserts (the Pb-B_4C bucket, the standard aluminum dosimetry bucket, the LP-1 bucket, and the boom box for neutron generator testing) were modeled. These cavity inserts were modeled to be easily added or removed by changing comment cards. The cavity inserts contain a transformation in the model that allows the inserts to be placed on the different pedestals described above.

7. Finally, a section was created for placing "externally created" experiment packages into the model. This section has a transformation card that allows an analyst to create a model and test the geometry external to the reactor model.

The general method used to construct the MCNP model of the ACRR has been described above. The following sub-sections give the details of each of the modeled components.

2.1.1. Regular and 90% Fuel Elements

Sixteen UO_2-BeO fuel disks (inner and outer pellets) are stacked and enclosed in a niobium cup 3.5408 cm in outer diameter and 10.846 cm in height, with a 0.0381 cm wall thickness (see Figure 1). The fuel stack height is 10.16 cm. The first pellet inserted in each cup maintains an outer diameter slightly smaller than for the standard pellet, 3.205 cm compared to 3.368 cm for the standard pellet. This allows for the cups to be stacked and snugly fit one on top of the other. The last cup includes an additional pellet. A niobium cap is fitted snugly to the top of the last loaded fuel cup. A loose fit is formed between the outer fuel pellet and the inner ridges of the fluted niobium cup, and between the outer ridges of the cup and the inner surface of the cladding. A nominal 0.025 cm gap exists between the outer fuel pellet and the inner ridges of the cup, and a nominal 0.025 cm gap between the cup outer ridges and the inner surface of the cladding.

The cladding is a stainless-steel tube 54.534 cm in length, 3.747 cm in outer diameter, with a 0.051 cm wall thickness. Five fuel-loaded niobium cups are stacked within the cladding for an effective fuel height of 52.25 cm. The top and bottom portions of the fuel element are loaded with solid BeO plugs that serve as neutron reflectors. These reflectors are held in place by the fuel element end caps. The fuel element is sealed at the top and bottom by welded end fittings. The end fittings are shaped to serve as locators for the elements within the top and bottom core grid plates and are tri-form shaped to allow for coolant flow through the grid. The top fitting has a pintle that allows for handling with a remote handling tool.

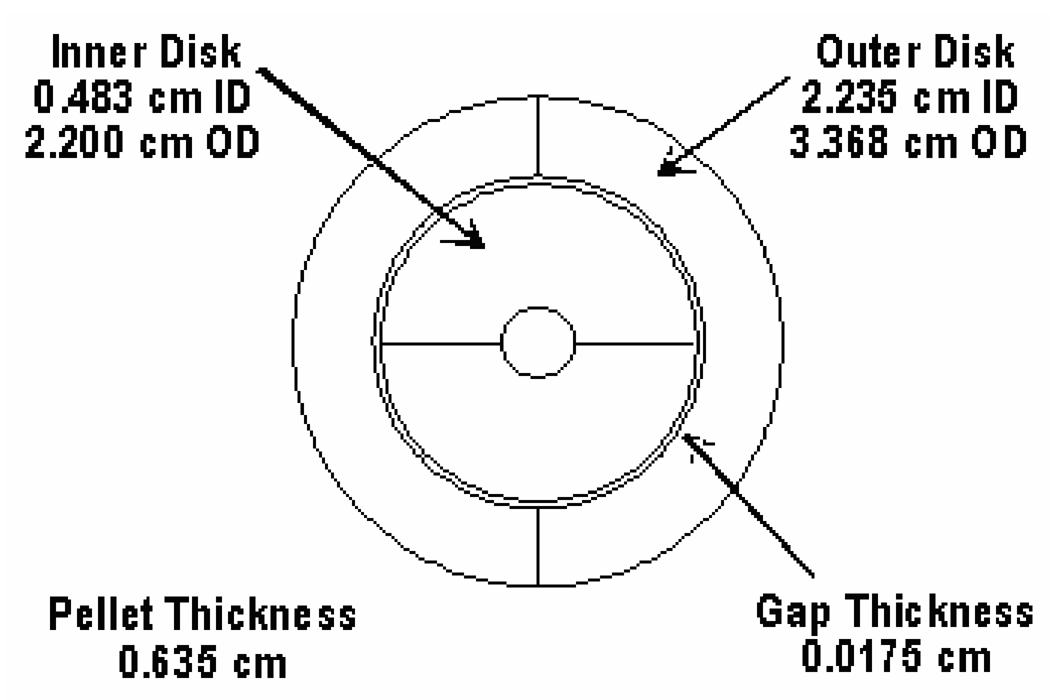

Figure 1. ACRR UO_2-BeO Fuel Pellet

Although the ACRR fuel is constructed in multiple segments (see Figure 1), the MCNP model of the fuel was produced as a simplified element. The inner and outer disks were modeled as one piece and the gap between them was ignored (see Figure 2). The density (3.3447 g/cm^3) and volume (455.9 cm^3) of the fuel in the regular fuel element were calculated to account for this simplification. The simplification results in a model fuel mass of 1524.99 grams. The safety analysis report for the ACRR (ACRR SAR) indicates that the fuel mass for a single rod is 1525 grams [Na99].

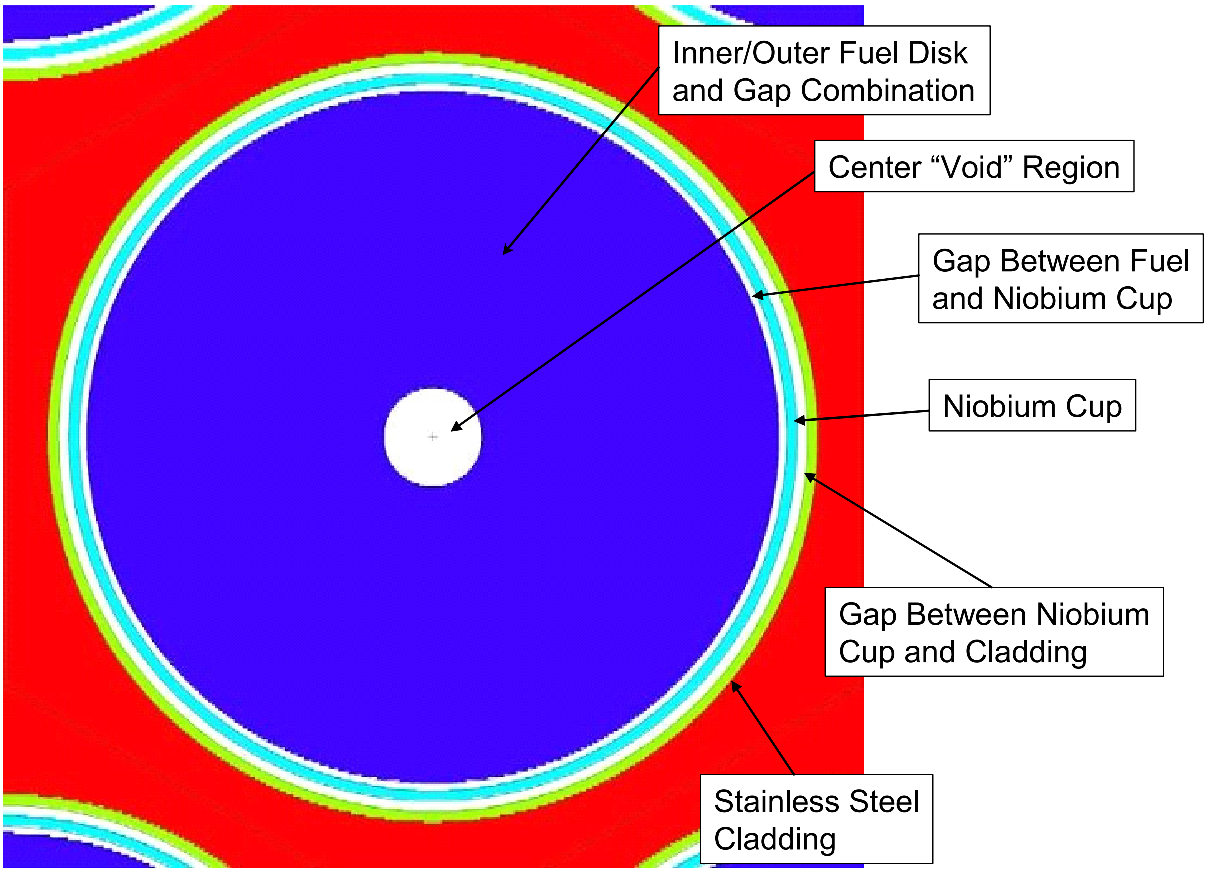

Figure 2. Cross-Cut of MCNP Model of ACRR UO_2-BeO Fuel

Figure 3 shows an ACRR fuel assembly. As noted above, the fuel assembly is constructed of five niobium fuel "cups" and clad with stainless steel. The MCNP model of the fuel element does not include the end caps of the niobium cups. The MCNP model includes the gaps, the "side" of the niobium cups, and the stainless steel cladding (note these "layers" in Figure 2). However, the shape of the BeO plug and top and bottom fittings are simplified in the model (see Figure 4).

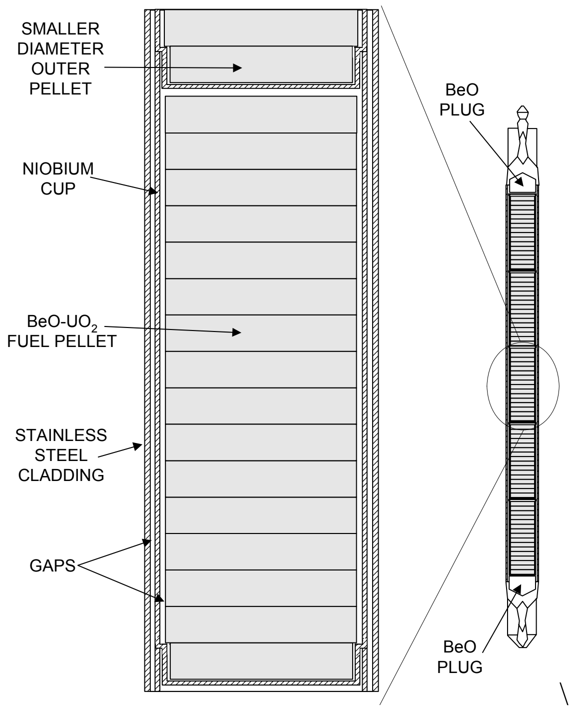

Figure 3. ACRR Fuel Element Assembly

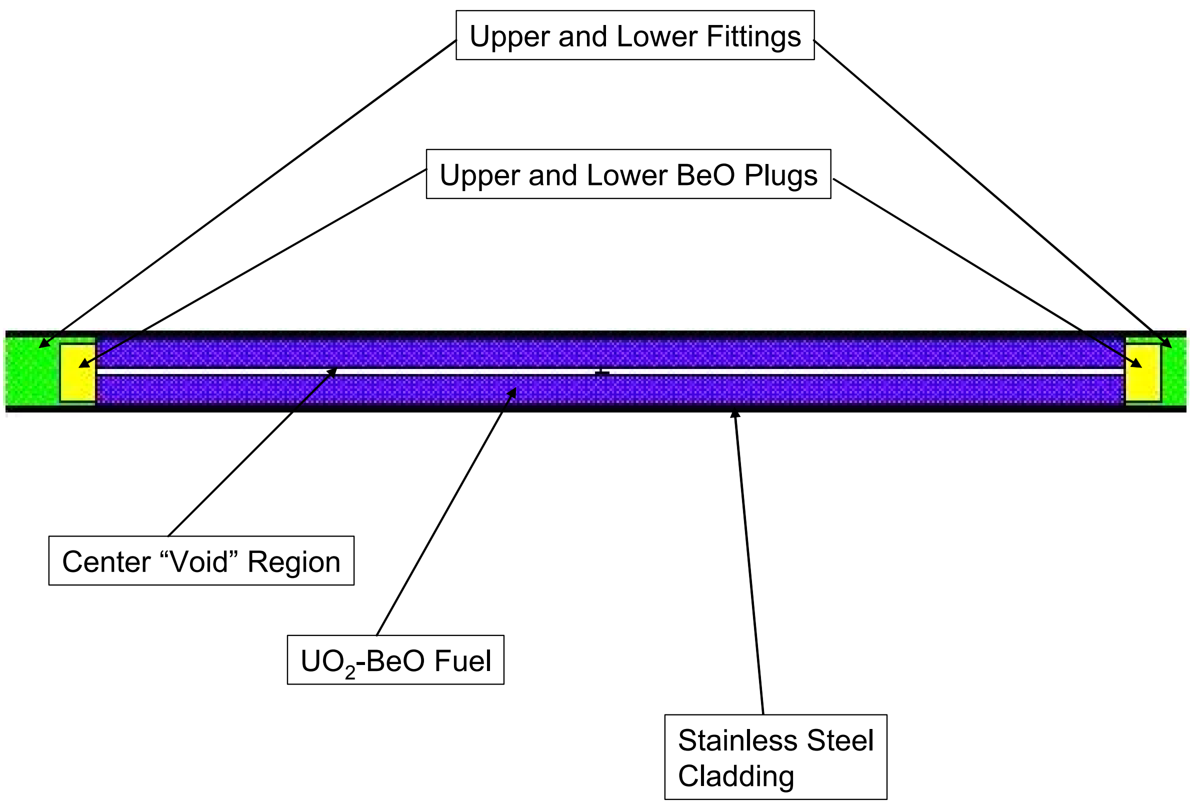

Figure 4. MCNP Model of ACRR Fuel Element Assembly

The 90% fuel elements are ACRR fuel assemblies with the fuel density reduced to 90% of that of the regular fuel assemblies. Thus, the 90% fuel elements are modeled in exactly the same manner as the regular fuel elements. The only change to the 90% fuel element is the density of the fuel. The density of the 90% fuel element is 3.0102 g/cm^3 (90% of 3.3447 g/cm^3). In addition, the instrumented fuel assemblies are assumed to be exactly the same as the regular fuel element (i.e., no special modeling for the instrumented fuel elements).

2.1.2. Fuel-Followed Control Rods

The ACRR has six control rods. Each control rod contains a fuel follower section and a neutron absorber (poison) section. The neutron absorber material is boron carbide (B_4C). The B_4C is in the form of pellets 2.921 cm in diameter stacked to a height of 52.25 cm. The absorber length is such that the absorber covers the entire active fuel height when inserted in the core. The B_4C rod is enclosed in a stainless-steel sleeve 52.25 cm in length and 3.49 cm in outside diameter, with a 0.24 cm wall thickness. The absorber section is followed by a UO_2-BeO fuel section (stacked pellets within niobium cups) identical to a fuel element. A stainless-steel magneform plug separates the absorber and fuel-follower sections. The fuel-follower provides an enhancement in the reactivity worth of a control rod. The rod assembly is held within a stainless-steel cladding approximately 163 cm in length and 3.747 cm outside diameter, with a 0.051 cm wall thickness. Thus, a control rod is identical to a fuel element in outside diameter. The absorber section is held in place with a stainless-steel plug and spacer sleeve. The fuel-follower section is held in place by a BeO reflector plug, a stainless-steel plug, and a spacer sleeve. The bottom end of the rod is sealed with a stainless-steel plug welded to the cladding. The top end is sealed using a stainless-steel plug. A schematic of a fuel-followed control rod is found in Figure 5.

The MCNP model of the fuel-followed control rods contains the same simplifications described above for the fuel section. The magneform plug is modeled, but the BeO reflector and the top fitting of the control rods are simplified as above. The poison section of the control rod is modeled as a uniform material of B_4C rather than as pellets. Figure 6 contains a figure of a MCNP model of the fuel-followed control rod. The MCNP model of this element contains a transformation card that allows the position of the control rods to be moved as a bank (the general method used to move the rods at the ACRR). This transformation also allows the two sections (poison and fuel) of the rod to be moved to the corresponding position of the actual rods during a reactor operation.

2.1.3. Fuel-Followed Safety Rods

The two safety rods are identical in design to the control rods with the exception that the B_4C neutron absorber pellets are 1.143 cm in diameter versus the 2.921 cm diameter pellets used in the control rods. The safety rods in the MCNP model reflect this change. In addition, another transformation card is used for the safety rods because the safety rods are not used in the same manner as the control rods. The safety rods are either fully withdrawn or fully inserted into the ACRR.

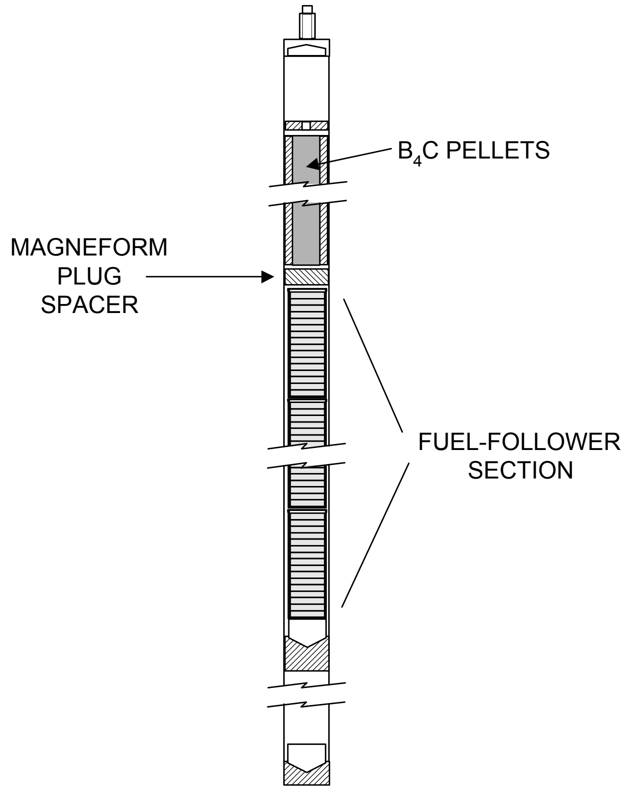

Figure 5. Fuel-Followed Control Rod Schematic

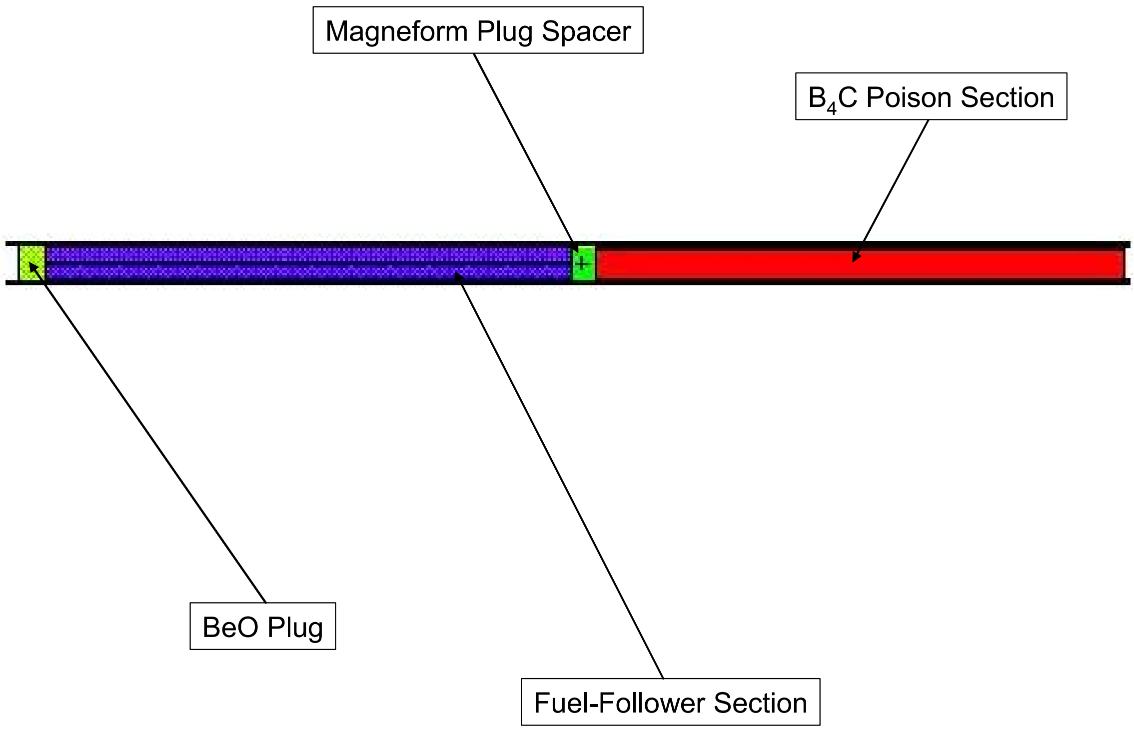

Figure 6. MCNP Model of Fuel-Followed Control Rod

2.1.4. Void-Followed Transient Rods

There are a total of three transient rods that are used in the core under normal operating conditions. In the steady-state mode, these rods remain as part of the control system and are used in a similar manner as the control rods. Figure 7 shows the design of the transient rod. The neutron absorber material is B_4C. The B_4C is in the form of pellets 1.763 cm in diameter stacked to a height of 76.2 cm. The absorber length is such that it covers 1.5 times the active fuel height when inserted in the core. The column of B_4C pellets is covered with two complete wraps of 0.0127 cm thick aluminum foil. The column is located in the top portion of the rod, held in place by a compression spring. A "void" section follows the absorber section. The absorber and void-follower sections are separated by a Al6061 spacer, supported from the bottom plug of the cladding by an aluminum spacer tube. The rod assembly is held within Al6061 cladding approximately 1.65 m in length and 2.54 cm outside diameter. The bottom end of the rod is sealed with an aluminum plug welded to the cladding. A welded end cap also seals the top end.

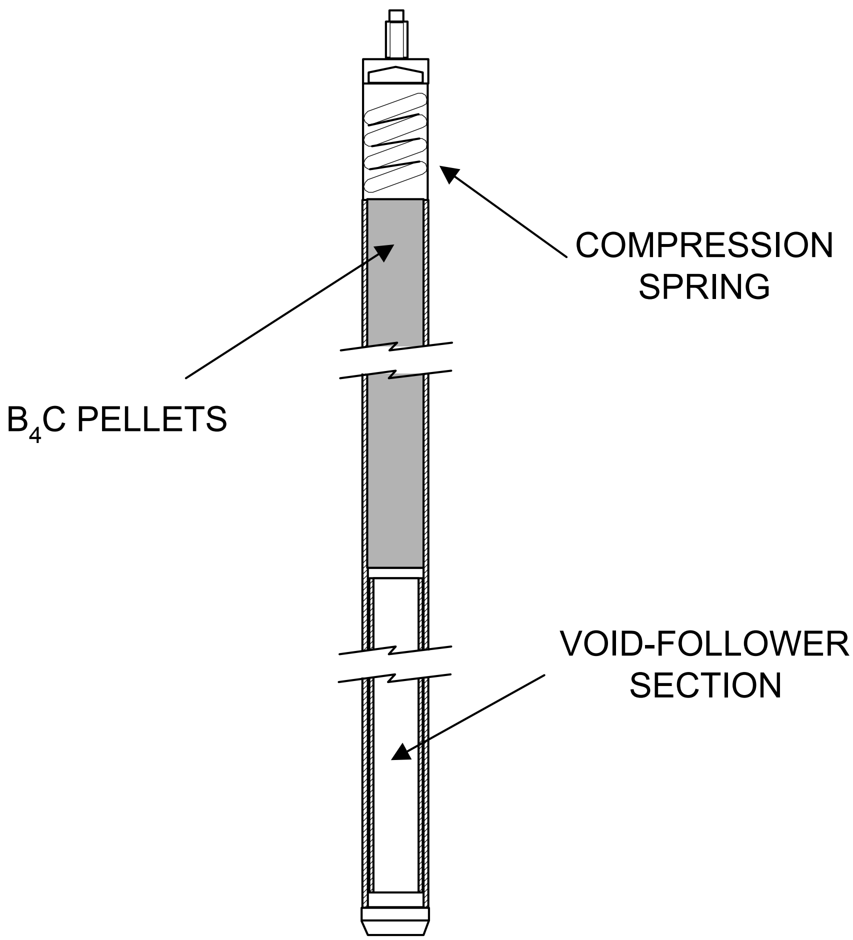

Figure 7. Void-Followed Transient Rod Schematic

The MCNP model of the void-followed transient rods contains some simplifications necessary for easy modeling. The compression spring is not modeled. The two thick aluminum foil wraps are modeled as single layer of aluminum. The poison section of the control rod is modeled as a uniform material of B_4C rather than as pellets. The aluminum spacer between the void section and absorber material is included in the model of the transient rod. Figure 8 contains a figure of a MCNP model of the void-followed transient rod. The MCNP model of this element contains another transformation card that allows the position of the transient rods to be moved to the proper location in the reactor.

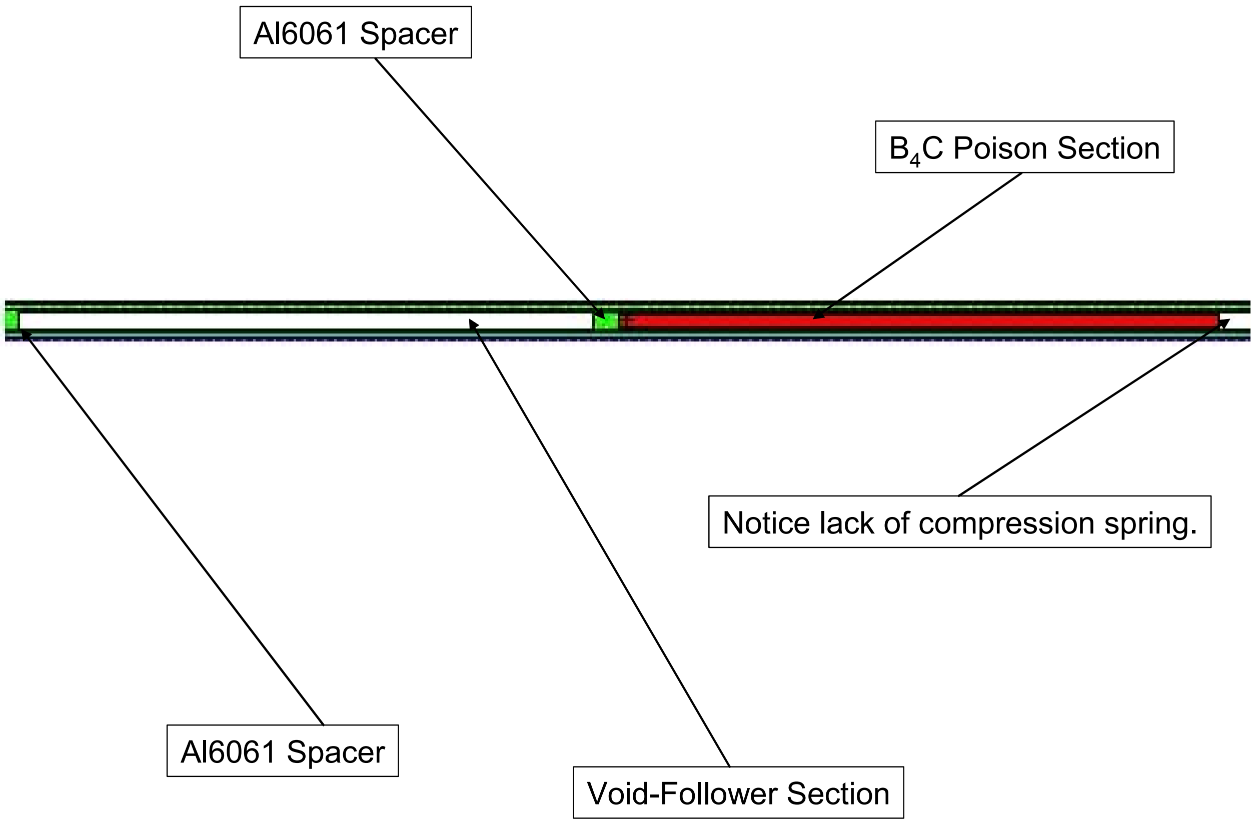

Figure 8. MCNP Model Void-Followed Transient Rod

2.1.5. Nickel Elements

The ACRR reactor core is surrounded by nickel "reflector" elements. These nickel elements are constructed so that their outside diameter is the same as the outside diameter of the stainless steel cladding of a regular fuel element. The MCNP model of these nickel elements assumes that the element is a right circular cylinder of the same height as the physical element. It also neglects the fittings on the top and bottom of the elements (exactly the same simplification as the fuel element model).

2.1.6. Aluminum (Void) Elements

The ACRR contains several elements that are essentially aluminum tubes with a void inside. These elements are modeled with the correct aluminum thickness for tube walls and a void (vacuum) inside the tube.

2.1.7. Water Elements

In order to produce the proper lattice structure for the MCNP model of the ACRR reactor core, water elements must be created. The ACRR has a standard 236-element "pulse configuration." The MCNP model must use 625 elements to properly model the 236 elements. These water elements are necessary to insure a complete "fill" of the 625 element model reactor core specification. The additional elements in the model are filled by these water-filled elements. (*NOTE: A lattice description of the reactor is not necessary, but it greatly simplifies the modeling of the reactor*.)

2.1.8. Reactor Core Configuration and Loading

The loading of the ACRR is found in Figure 9. The figure shows the six-ring configuration of fuel elements surrounding the hexagonal cavity. The third ring contains the control, transient, and safety rod locations. The core is surrounded by nickel reflector elements and plates. Using the model elements described in the previous sections, the MCNP model of the reactor core configuration was constructed. The fuel loading in the model reflects the configuration found on the ACRR "board" as of May 2003. The model uses a right hexagonal prism (RHP) to establish the boundary of the core (see Figure 10). The green elements inside the RHP are the water elements (one can see in the figure why they are necessary). The yellow elements surrounding the reactor core are the nickel reflectors. The fuel elements are dark blue (regular fuel) and light blue (90% fuel). The white elements in the external portion of the reactor core are the aluminum (void) elements while the white elements in the interior of the core are void portion of the transient rods. The orange elements in the interior of the core are the control rods. The two safety rods in this view of the model appear exactly like the regular fuel elements since the rods are in the "up" position.

The other features of the reactor core found in Figure 10 are described in detail in the following sections. In the center of the figure is the central cavity. The lower portion of the core (yellow rectangle) is the nickel reflector plate that "decouples" the ACRR from the FREC. The upper right portion of the reactor model in Figure 10 is the window to the neutron radiography facility. The structural components of the neutron radiography facility, at the fuel level, are also seen in that portion of reactor model.

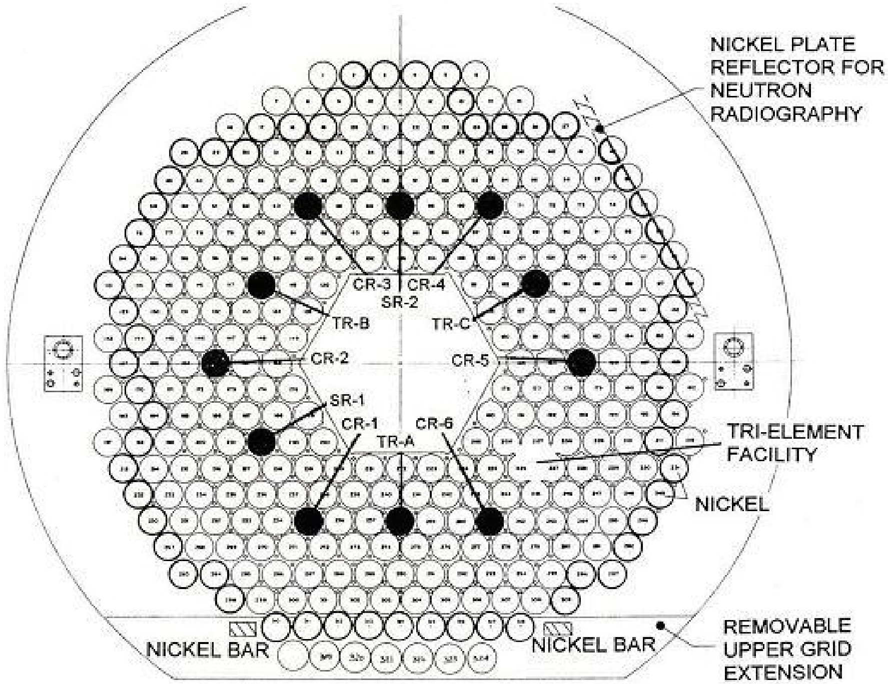

Figure 9. ACRR Standard 236 Element Core Loading

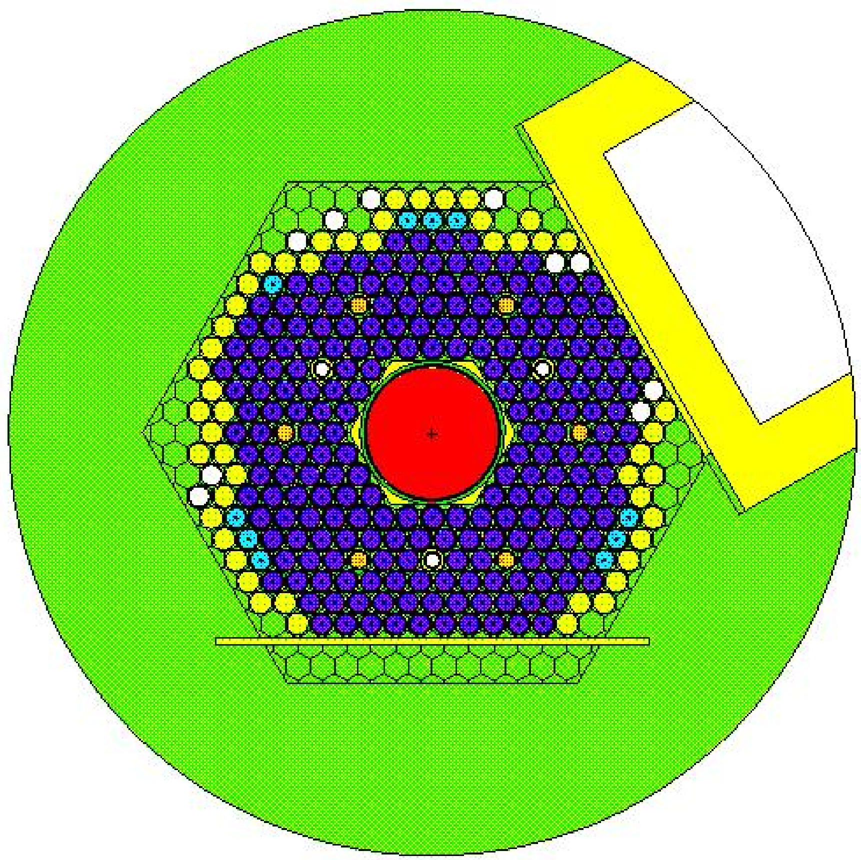

Figure 10. MCNP Model of ACRR Core

2.1.9. Central Cavity

The most prominent feature of ACRR is the large (23.3 cm inside diameter) dry, central irradiation cavity at the center of the core. The central irradiation space is formed by hexagonal cutout in the upper and lower core grid plates (described below in "External Features" section) across the flats of the hex. The space allows installation of experiment assemblies at the center of the core where neutron flux levels are highest. The "new" central cavity is a stainless steel cavity liner with aluminum "corners" to produce its RHP shape. A schematic of the central cavity is found below in Figure 11. Figure 11 is also a presentation of the MCNP model of the central cavity.

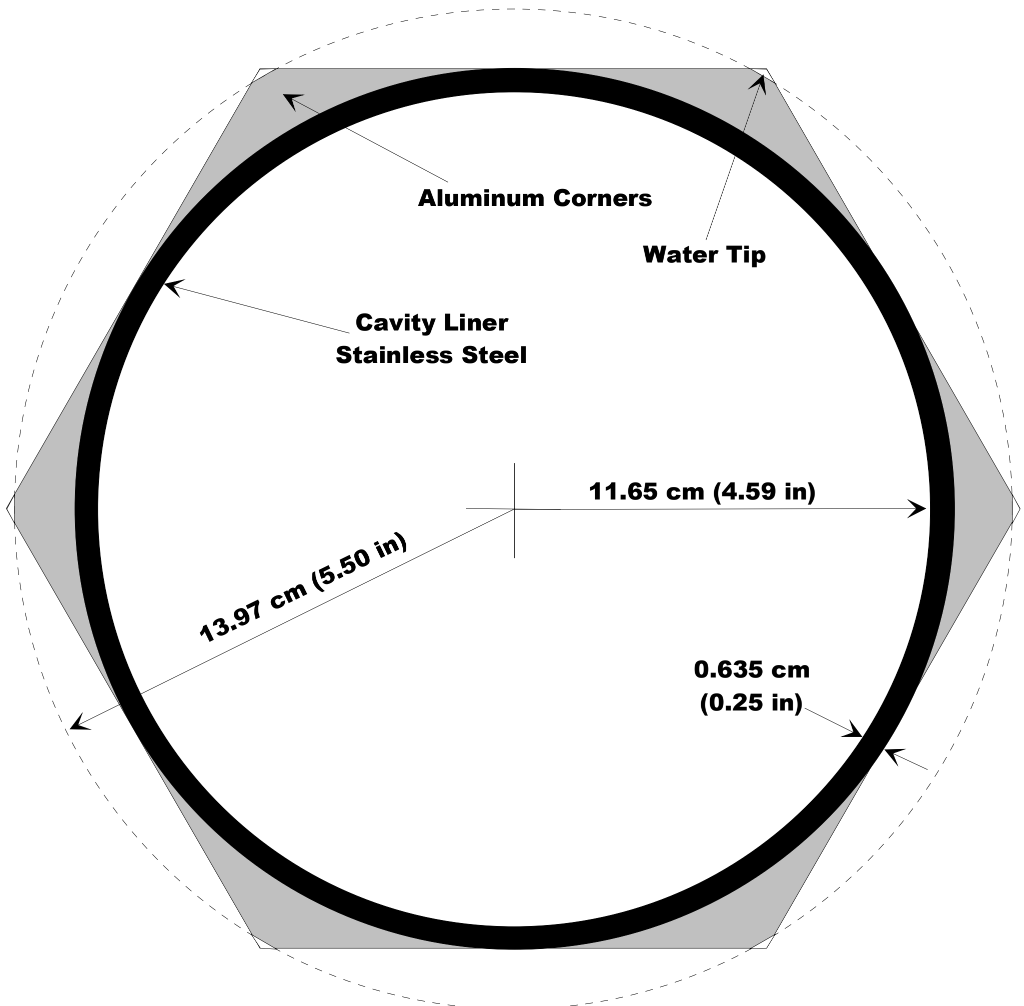

Figure 11. Schematic/MCNP Model of Central Cavity Liner

2.1.10. Central Cavity Additions

The usable depth of the central irradiation cavity can be altered by changing the height of a pedestal resting on the bottom of the tube. For general experimenter use, there are two pedestals (32 inch [32"] and 8 inch [8"]) that are used together to adjust the position of experiment packages. Experiment packages are generally located at the fuel centerline so that the irradiation conditions are as uniform as possible. The pedestals are constructed of aluminum and are designed to support in excess of 1000 lbs. The two widely used configurations of pedestals are the 32" pedestal and the combination of the 32" + 8" pedestals. Figure 12 below presents a view of the combination of the two pedestals. The MCNP model contains the capability of rapid changes between the configurations and instructions on how to make those changes.

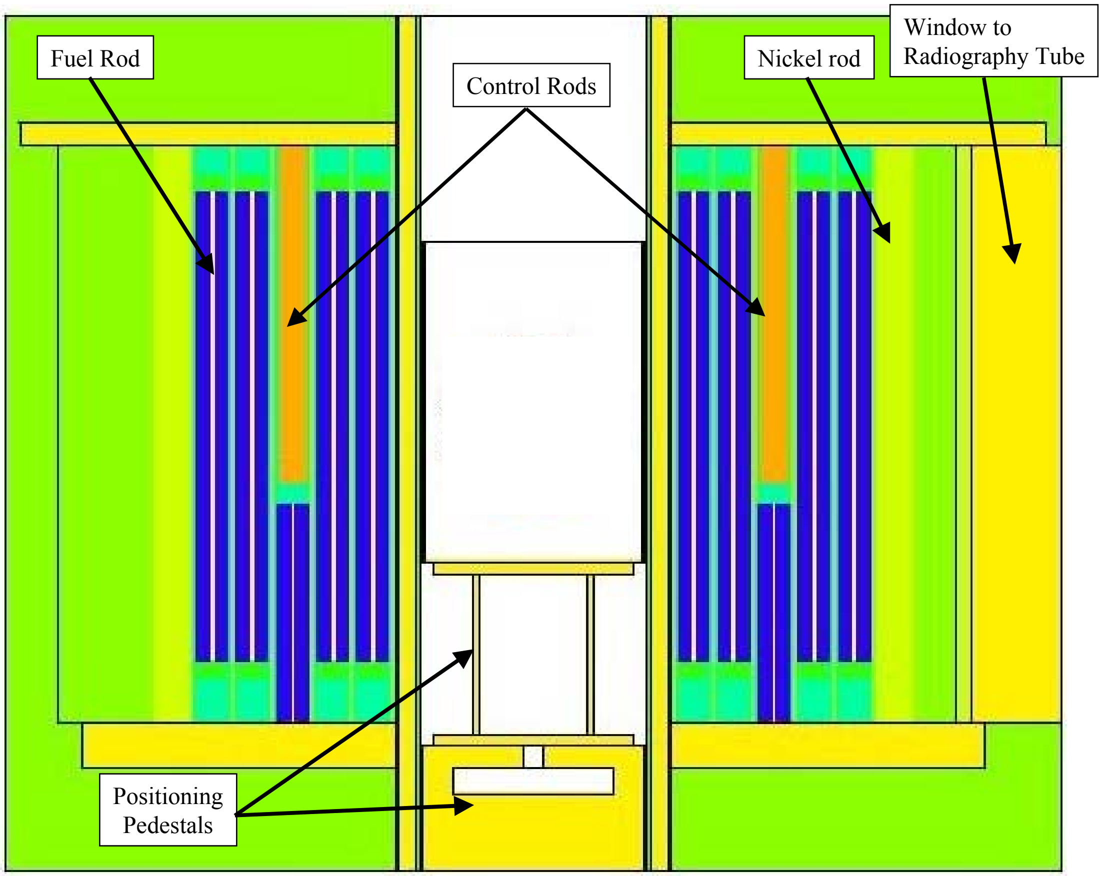

Figure 12. View of Positioning Pedestals in ACRR Model

2.1.11. External Features

The top and bottom grid plates of the reactor core are designed based on the requirements found in the ACRR SAR [Na99]. The grid plates in the MCNP model contain simplifications of these design requirements that do not effect the radiation transport of the model. The simplifications are basically the elimination of the alignment holes for the fuel elements. These simplifications are complementary to those made for the fuel and control elements.

The nickel plate, window to the neutron radiography tube (see Figure 10 and Figure 12), and the FREC side nickel plate (see Figure 10) are found in the MCNP model. Again, the designs of these features are based on the requirements found in the ACRR SAR [Na99]. The MCNP models of these features match the "as built" equipment very closely.

2.1.12. *Central Cavity Inserts (Buckets)*

There are several central cavity inserts or experiment buckets that are typically used by experimenters at the ACRR. Four of these inserts are currently part of the standard MCNP model of the ACRR: (1) Standard aluminum dosimetry bucket; (2) Lead-Boron (Pb-B_4C) bucket; (3) Lead-Polyethylene (LP-1) bucket; and (4) Boom box for neutron generator (NG) testing. The descriptions of each of these inserts are found in the individual experiment plans. The experiment plan numbers for the inserts are seen in Table 1.

Table 1. Experiment Plan Numbers for Cavity Inserts

Central Cavity Insert	ACRR Experiment Plan Number
Standard Aluminum Dosimetry Bucket	Covered as a Class I experiment
Lead-Boron (Pb-B_4C) Bucket	EP #841*
Lead-Polyethylene (LP-1) Bucket	EP #927*
"Boom-box" for NG Testing	EP #939*
*The relevant sections of these experiment plans are found in Appendix C.	

The aluminum dosimetry bucket was modeled as concentric right circular cylinders such that the thickness of the aluminum wall is correctly rendered. However, the wire handle of the bucket is not included in the model. The model contains a transformation card so that the aluminum bucket may be placed on either the 32" pedestal or the combination of the 32" + 8" pedestals.

The Pb-B_4C bucket was modeled according to the engineering drawings on file at the ACRR facility (see Appendix C). The standard density of the B_4C is 2.48 g/cm^3. However, the construction of the bucket used B_4C powder. Thus, the standard density could not be achieved. When the geometric model of the Pb-B_4C bucket was completed, the density of the B_4C in the model was reduced to insure that the model weight of the bucket agrees with the physical bucket (~202 kg or ~446 lbs). The MCNP model of the Pb-B_4C bucket is seen in Figure 13. The model contains a transformation card so that the Pb-B_4C bucket may be placed on either the 32" pedestal or the combination of the 32" + 8" pedestals.

The LP-1 bucket was modeled according to the engineering drawings on file at the ACRR facility (see Appendix C). The MCNP model of the LP-1 bucket is seen in Figure 14. The model contains a transformation card so that the LP-1 bucket may be placed on either the 32" pedestal or the combination of the 32" + 8" pedestals.

The boom box for neutron generator testing was modeled according to the engineering drawings on file at the ACRR facility (see Appendix C). The MCNP model of the boom box is seen in Figure 15. The model contains a transformation card so that the boom box may be placed on either the 32" pedestal or the combination of the 32" + 8" pedestals.

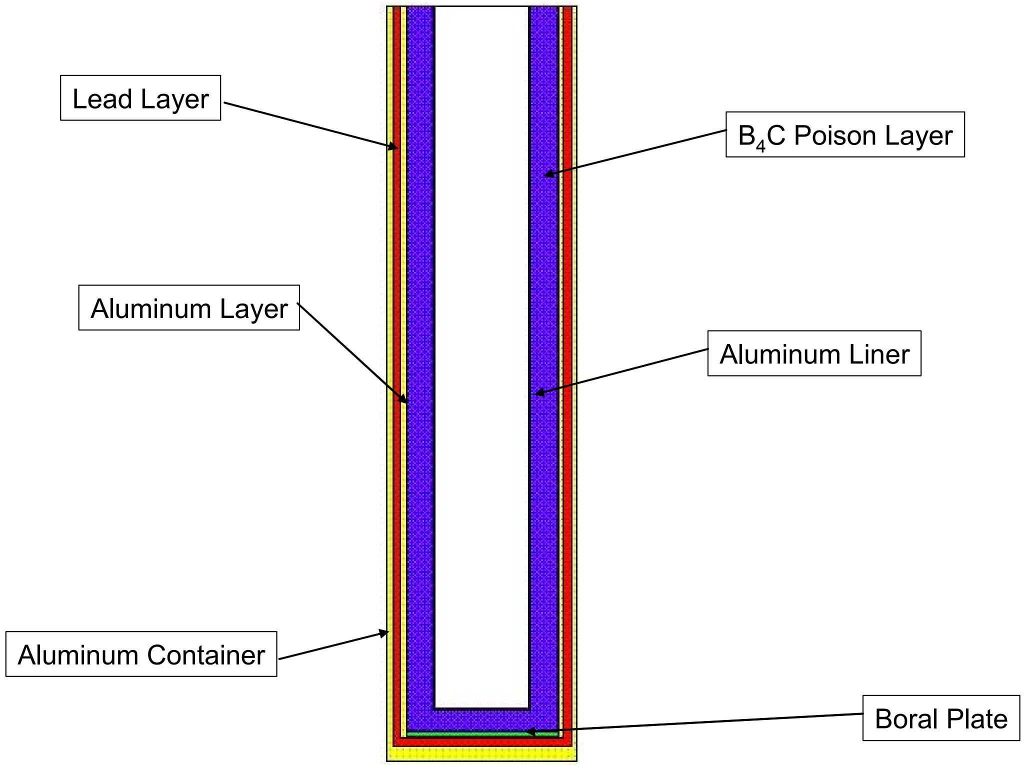

Figure 13. MCNP Model of Pb-B_4C Bucket

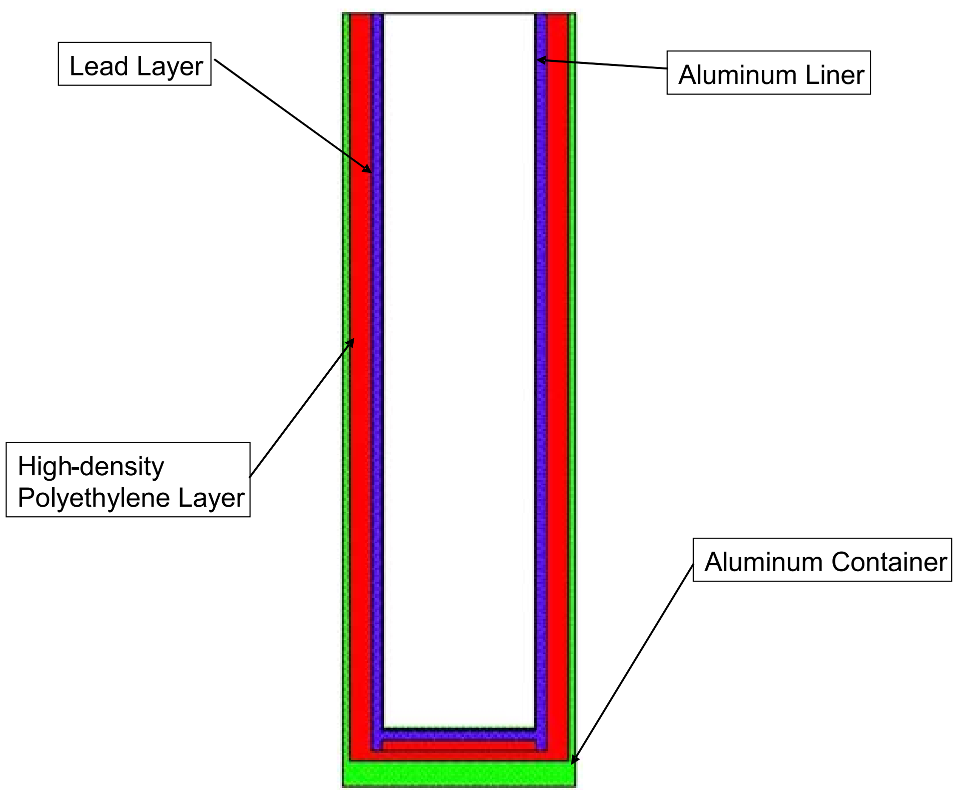

Figure 14. MCNP Model of LP-1 Bucket

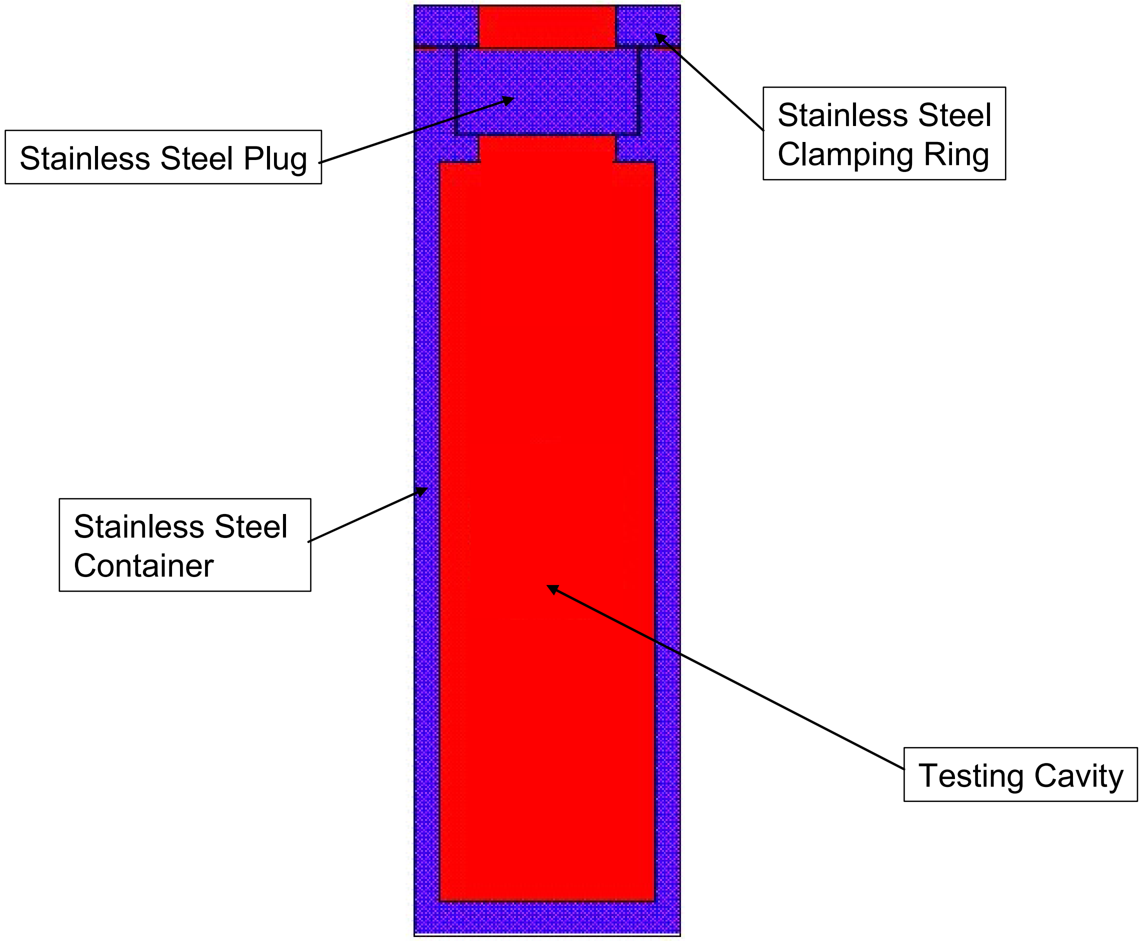

Figure 15. MCNP Model of Neutron Generator Boom Box

2.1.13. Experiment Packages

The MCNP model of the ACRR contains a special section for placing "externally created" experiment packages easily into the model. If the experiment packages are modeled with appropriate cell and surface numbers (1000-2999) and a transformation card (*TR6), then the external model will go into the ACRR model with very little effort. This feature allows the geometry of the experiment package to be tested before increasing the computational overhead required when testing the geometry inside the reactor model.

2.2. ACRR With FREC-II Coupled

The MCNP model of ACRR with the FREC-II coupled starts with the previous section as a base. The first modification to the model is to remove the FREC side nickel plate so that the FREC can be mated to the ACRR. The rest of the process for creating the FREC model was very similar to that used to create the ACRR model. The fuel elements for FREC (both nominal and raised) were created as lattice elements. In addition, the regulating rods and water elements were then produced. A core for the FREC was then modeled and filled with the proper lattice elements. Finally, the FREC cavity, void chambers, and grid plates were modeled.

The general method used to construct the MCNP model of the ACRR coupled to FREC-II has been described above. The following sub-sections give the details of each of the modeled components.

2.2.1. Nominal and Raised FREC Fuel Elements

The FREC-II fuel elements are the U-ZrH fuel elements originally used in the Annular Core Pulse Reactor (ACPR) and removed from it in 1977 [Na99]. The fuel-moderator material selected for the ACPR consists of delta-phase zirconium hydride moderator homogeneously combined with enriched uranium fuel. The fuel alloy body formed from this material is 38.1 cm in length by 3.56 cm in diameter and contains 12 weight percent uranium. The 12 weight percent uranium is enriched to 20 weight percent in ^{235}U isotope (about 53.4 g). Thus, the volume of the hollow, cylindrical fuel-moderator material in each element is 367 cm^3. Graphite cylinders 3.5 cm in diameter by 8.5 cm in length are added to both ends of the fuel-moderator assembly to enhance neutron reflection. Figure 16 shows the internal components of the fuel element assembly.

The cladding structure surrounding internal components is made of stainless steel tubing with walls 0.051 cm thick, as are the end fittings to which the cladding is welded. The outside diameter of the fuel element (cladding structure) is nominally 3.747 cm with a nominal 0.043-cm thick annular space between the cladding and the fuel-moderator body. The gap is maintained during expansion of the fuel material by a shallow dimple design in the surface of the cladding. The fitting at the upper end of the fuel element has a grooved protuberance, especially shaped to fit and lock into a fuel-handling tool, and a triflute and spacer ring assembly which positions the element in the upper grid plate and permits the flow of cooling water through this grid.

As with the regular fuel elements of the ACRR, some simplifications of the nominal fuel elements were necessary. The upper and lower triflutes were simplified, but the rest of the element was modeled very close to the description given above and seen in Figure 16. Figure 17 displays the MCNP model of the nominal FREC-II fuel element.

The raised fuel elements are identical in the MCNP model with the exception of a transformation card that lifts the elements to the proper height in the model. The raised elements are present in the FREC-II to insure that the mating with the ACRR is done properly. Additionally, the instrumented fuel elements in the FREC were not modeled separately.

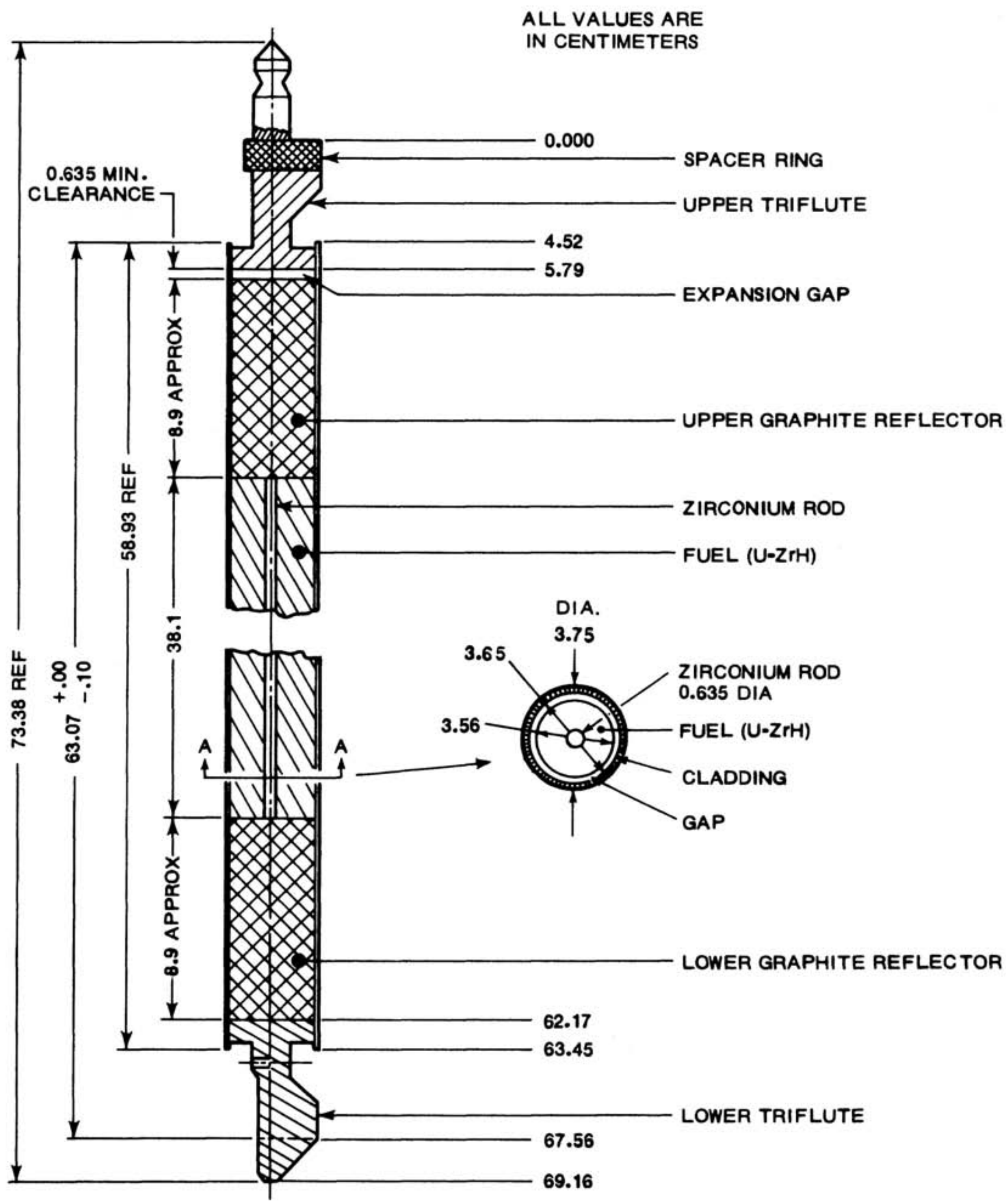

Figure 16. FREC-II Fuel-Moderator Element

2.2.2. FREC Regulating Elements

The design basis for the FREC rods is the same as was used for them as the control rods in the ACPR. They are designed to have a poison section (B_4C) and are fuel-followed. The total of four rods will be located in groups of two at the approximate center of the symmetric fuel regions near the back of FREC-II.

The FREC rods are designed to be easily moved full stroke within a specified location in the core between the upper and lower grid plates. Their reactivity worth is designed to be in the range of a few dollars per rod when the FREC-II is considered by itself and much less when combined with the ACRR. The FREC rods will not be used for making reactivity adjustments during operation with the reactor critical. They will function in a manner similar to the ACRR safety rods and will always be present in the operational configuration. The FREC rods may be pre-positioned in an intermediate vertical location to adjust the front to back neutron fluence. They are not essential to the overall system since the ACRR will drive the FREC-II. The most important use of the FREC-II rods will be for providing extra negative reactivity during loading or unloading of an experiment in the FREC-II or when FREC-II is not being utilized.

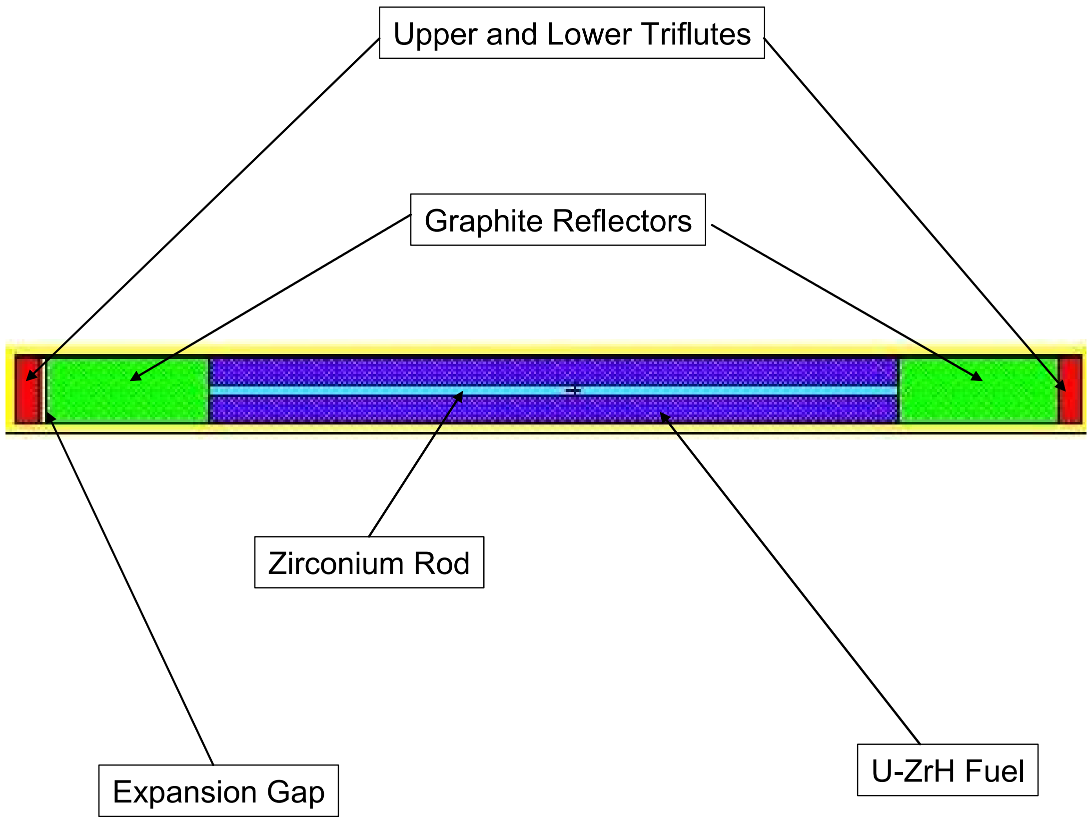

Figure 17. MCNP Model of FREC-II Fuel Element

The FREC-II fuel-followed regulating rod (FREC rod) is shown in Figure 18. Each FREC rod contains a length of fuel-moderator material identical to that in the standard fuel element, except that it is about 5 percent shorter. It is positioned in the rod below the poison (B_4C) section of the rod such that the reactivity effect of removing the poison as the rod is withdrawn is augmented by the simultaneous insertion of the fuel-follower section. The cladding of these elements, although longer and terminated differently, is similar to that of the standard element. The extra length of the FREC rods is taken up in an air filled section as shown in Figure 18.

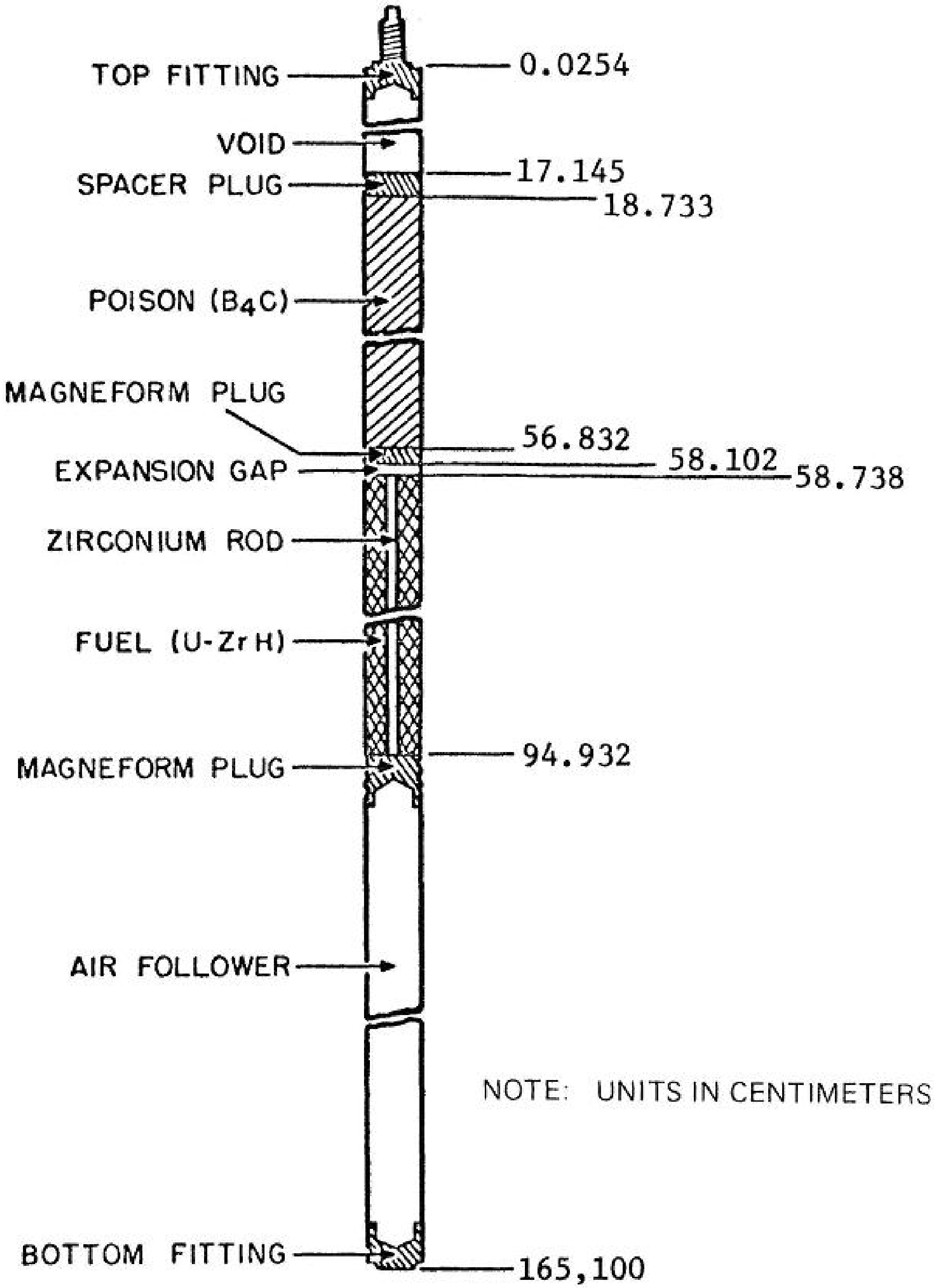

Figure 18. FREC-II Regulating Rod

Once again, there are some simplifications in the MCNP model of the regulating elements. Figure 19 shows the MCNP model. The top and bottom fittings are simplified. The model contains a transformation that allows the regulating rods to be moved as a bank to the proper position in the FREC model.

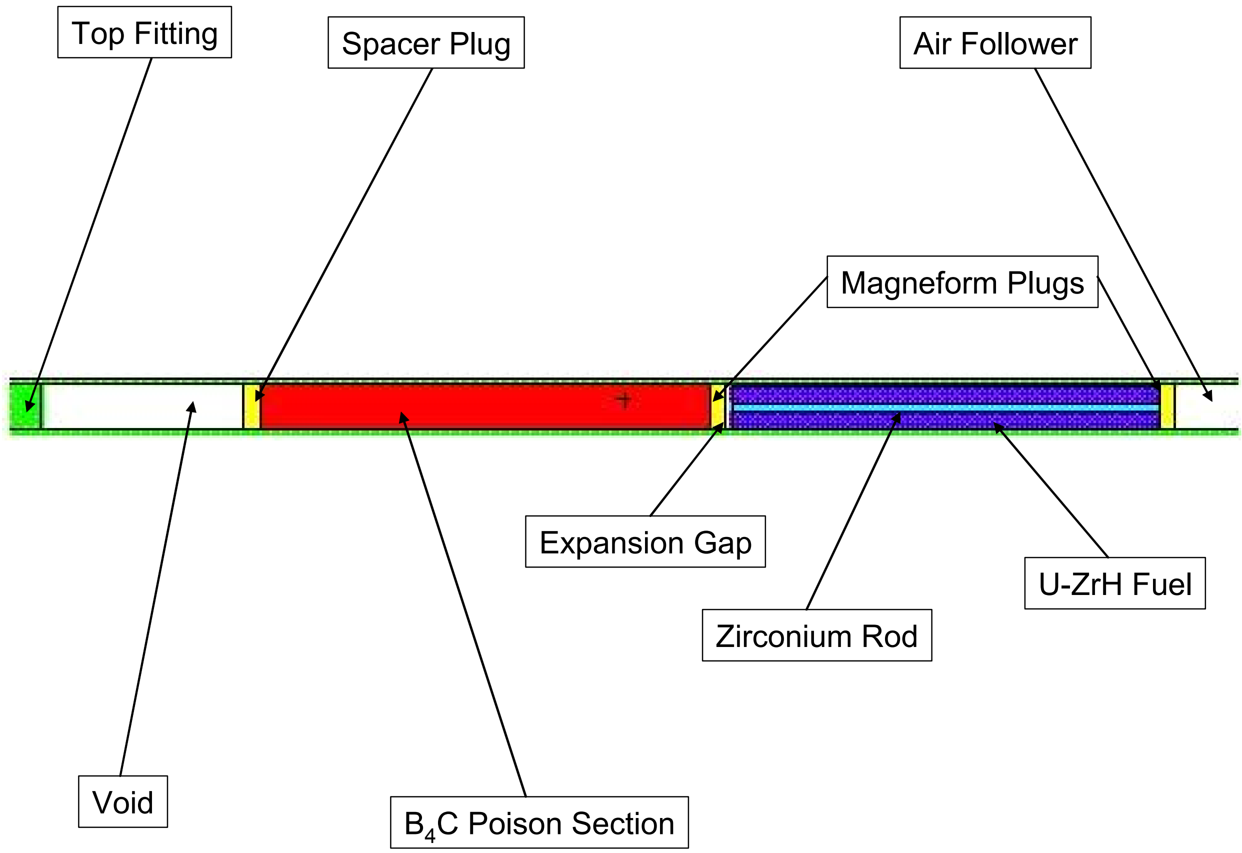

Figure 19. MCNP Model of FREC-II Regulating Rod

2.2.3. Water Elements
In order to produce the proper lattice structure for the MCNP model of the FREC core, water elements must be created. The FREC core has locations for 182 fuel elements and void chambers. The MCNP model must use 992 elements to properly model the 182 fuel locations. These water elements are necessary to insure a complete "fill" of the 992 element model reactor core specification. The additional elements in the model are filled by these water-filled elements.

2.2.4. FREC Core Configuration and Loading
The loading of the FREC-II core is found in Figure 20. The figure shows the FREC-II coupled to the ACRR. The regulating rod locations are seen in the figure. Using the model elements described in the previous sections, the MCNP model of the reactor core configuration was constructed. The model uses a RHP to establish the boundary of the FREC as it is coupled to the RHP of the ACRR model (see Figure 21). The other features of the reactor core found in Figure 21 are described in the following sections. However, one can identify the FREC cavity and void chambers in the MCNP model. Note that the nickel reflector plate that "decouples" the ACRR from the FREC has been removed.

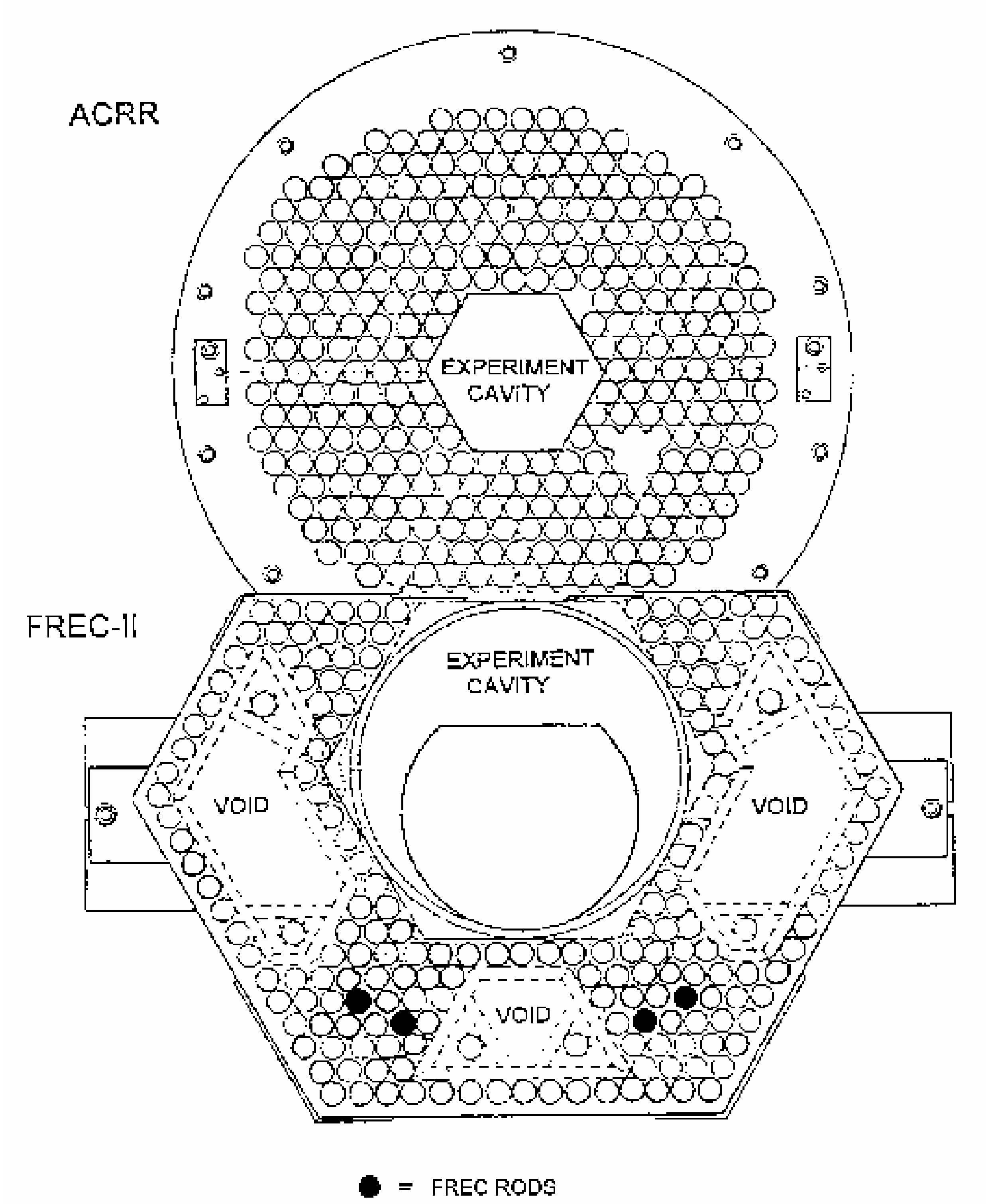

Figure 20. The ACRR and FREC-II Cores at the Fuel Level

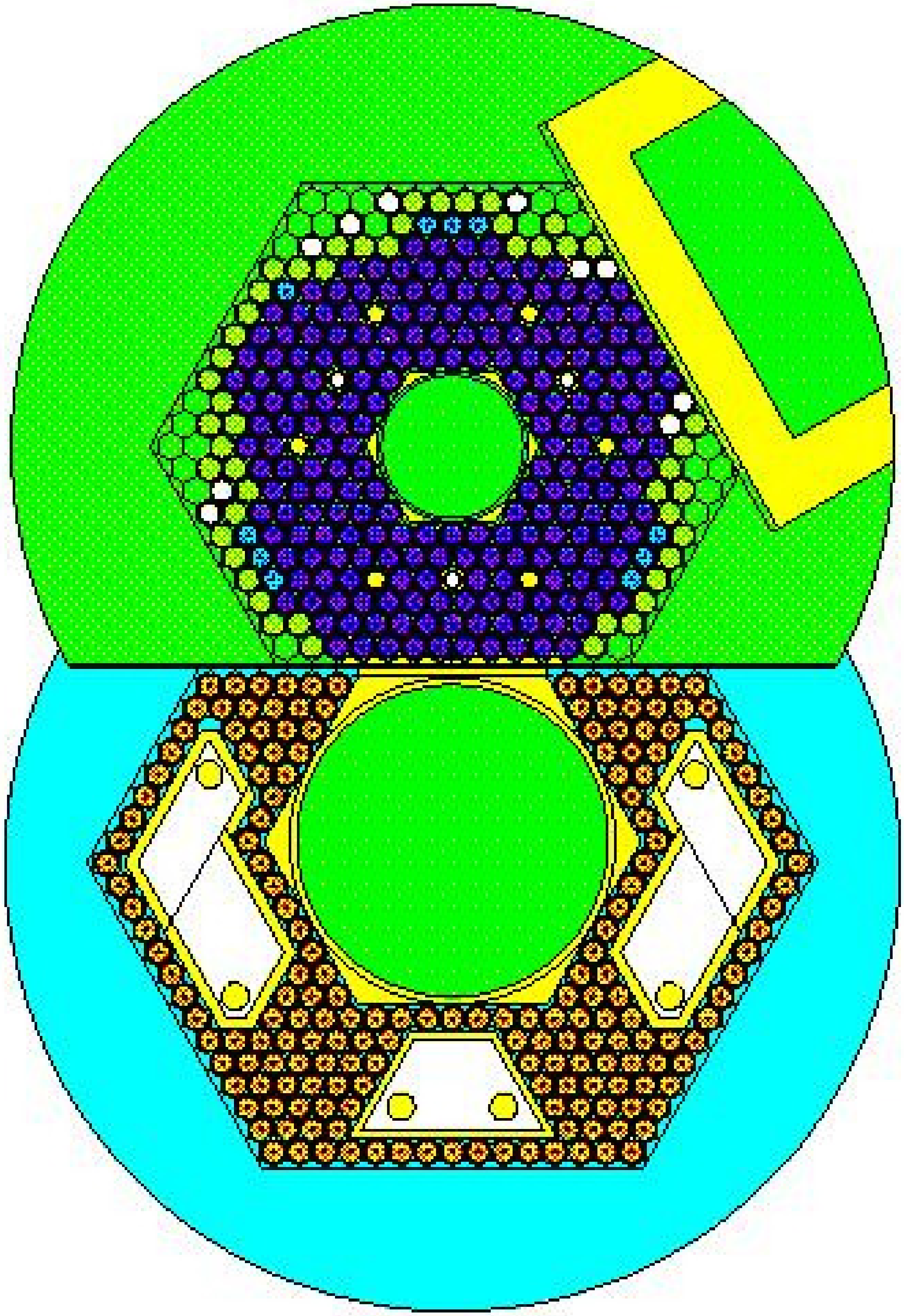

Figure 21. MCNP Model of the ACRR and FREC-II Cores

2.2.5. FREC-II Cavity

The FREC-II cavity or main tube is an aluminum tube with a nominal inner diameter (ID) of 50.8 cm, a nominal wall thickness of 1.27 mm, and a nominal inside height of 696 cm. The radial tolerances were strictly applied over the upper 365.8-cm section, since it accommodates the shield plug; the minimum measured inner diameter of this section is 50.5 cm and the maximum is 50.51 cm. The floor of the tube is an aluminum plate with a 35.56-cm penetration that can be blocked off with a circular aluminum disk to make a smooth floor across the tube at that point. The vertical location of this floor corresponds to the bottom of the ACRR core.

The MCNP model of the FREC-II cavity was modeled according to the above description. The cavity in the model can be clearly seen in Figure 21.

2.2.6. FREC-II External Features

The FREC-II upper fuel grid plate is made of 2.54 cm thick aluminum. It has holes of various diameters that can accommodate fuel rods, fuel-followed FREC rods, or nuclear instrumentation such as self-powered cadmium detectors. The FREC-II lower grid plate is also aluminum, with a thickness of 3.81 cm. The location of its holes corresponds to those in the upper plate. Thirty of the holes are enlarged to accommodate present and possible future FREC rods. Fuel elements can be fitted in the enlarged holes with small aluminum cups. The lower plate will carry the weight of the fuel, which is a fuel loading of 182 U-ZrH elements.

The upper and lower grid plates contain many more pairs of holes than for the 182 U-ZrH elements and four fuel-followed FREC regulating rods. The unused holes are blocked by the three aluminum void chambers located between the grid plates on the sides and rear of the FREC. These chambers channel neutrons from the ACRR to the symmetric fuel clusters on the backside of FREC-II. The three void chambers were sized to block the grid holes and thus prevent installation of the final few fuel elements to make FREC-II critical. As a consequence, FREC-II alone is always sub-critical.

All of these features are included with great detail in the MCNP model. In fact, the detail of the model can be seen by comparing the model of the FREC that is displayed in Figure 21 with schematic of the FREC that is found in Figure 20.

2.3. Material Cross Sections

The MCNP model of the ACRR uses the best available cross section data. For the fissile/fissionable isotopes in the ACRR, this corresponds to the ENDF/B-VI cross sections that include the delayed neutron treatment in the evaluations. The other isotopes in the model generally use the latest ENDF cross sections. However, when ENDF files are not available, the "best" available cross section is used. (In this sense, the "best" available cross section is chosen by the model developers/analysts.)

3. REACTIVITY WORTH CURVES

3.1. Control Rod Calibration Comparison

During the recent (1999) conversion of the ACRR from an isotope production (IP) configuration to the current pulse (or standard) configuration, the original dry central cavity was replaced. (The IP configuration in the following discussion is included only for comparison. None of the calculations presented used the IP configuration.) As a consequence of this replacement, the ACRR facility staff performed experiments to produce a control rod bank differential worth curve for use with the new central cavity. An integral worth curve for the control rod bank was also produced during this experiment. The same experiment was performed when the ACRR was originally converted from the standard configuration to the IP configuration.

Using the MCNP model with an empty central cavity (i.e., no pedestals or inserts), an integral worth curve for the control rod bank was produced. To produce the worth curve, the value for k_{eff} was calculated for a control rod position. The value of k_{eff} was converted to reactivity using the following equation:

$$\rho(\$) = \frac{k_{eff} - 1}{k_{eff}} \cdot \frac{1}{\beta_{eff}} \qquad (1)$$

where $\rho(\$)$ is the reactivity in dollars and β_{eff} is the effective delayed neutron fraction. (NOTE: The historical value of 0.0073 has been used for β_{eff}.) After calculating the reactivity for a control rod position, the difference ($\Delta\rho$) between two control positions is determined. The sum (integral) of these differences produces the calculated integral worth curve for the model. The integral worth curve consists of the following data set: Integral worth (in units of dollars of reactivity) as a function of z (in control rod units). This integral worth curve is compared to the two experimental integral worth curves described above. The comparisons are found in Figure 22 along with numerical fits to both the experimental and calculated reactivity curves. The technique and equation used for the numerical fits are found in the next section.

3.2. Calculated Worth Curves

The numerical fits to the curves found in Figure 22 are based on perturbation theory. Using the form of the "differential worth" definition found in Duderstadt and Hamilton [Du76], an equation for an offset differential worth curve is found in Eqn (2):

$$\frac{d\rho}{dz'} = A\sin^2[a(z_1 - z')] = A/2\{1 - \cos(2a[z_1 - z'])\} \qquad (2)$$

where A, a, and z_1 are parameters used for the numerical fit.

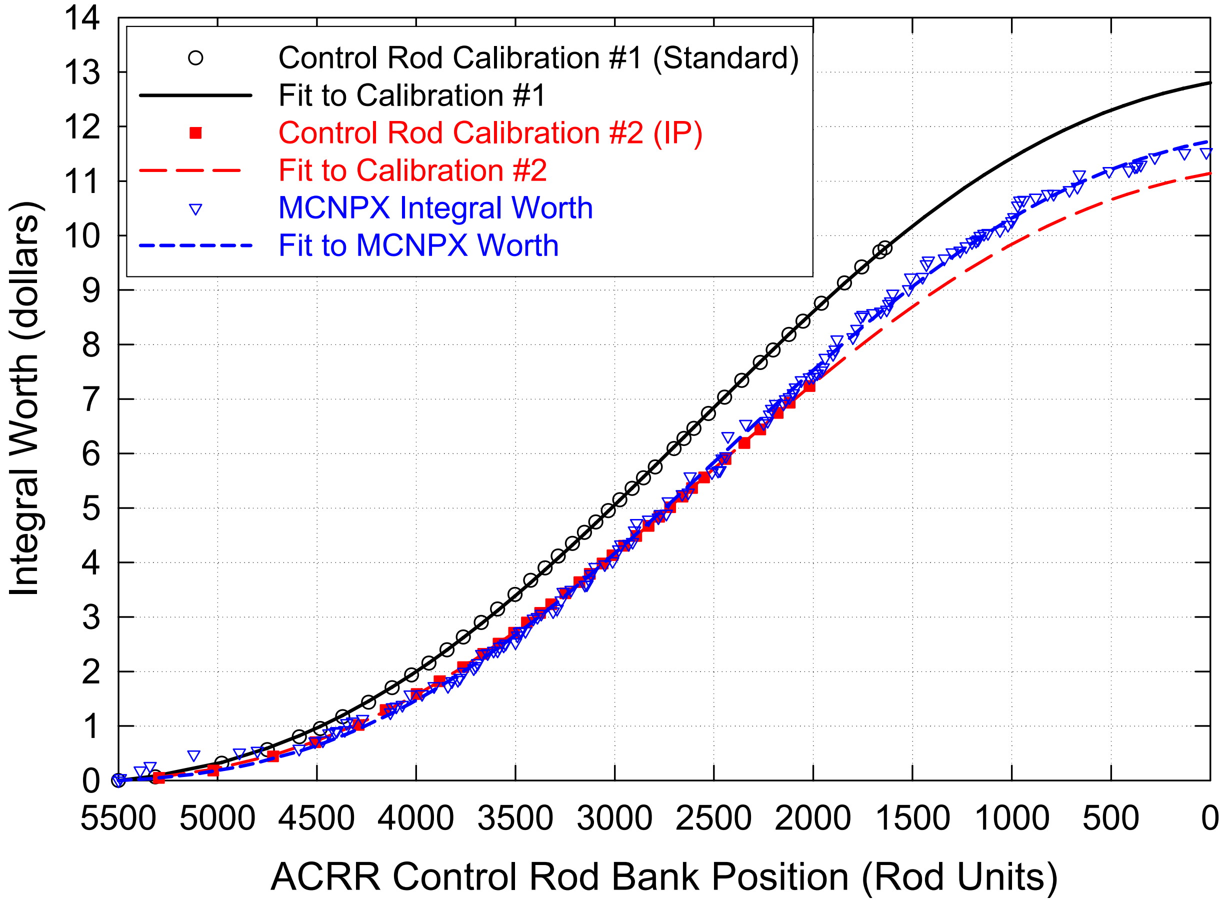

Figure 22. Control Rod Bank Worth Comparisons

In order to produce an integral worth curve, the integration found in Eqn (3) was performed:

$$\int_{z_0}^{z} d\rho = \int_{z_0}^{z} A \sin^2[a(z_1 - z')]dz' \tag{3}$$

where z_0 is equal to the length of the control rod bank movement (z_0 = 5500 rod units, z = 0 rod units corresponds to the control rod bank fully out, and z = 5500 rod units corresponds to the control rod bank fully inserted). The result of the integration of Eqn (3) is found in Eqn (4):

$$\rho(z) = A/2 \left\{ (z - z_0) + \left(\frac{1}{2a}\right)\left(\sin(2a[z_1 - z]) - \sin(2a[z_1 - z_0])\right) \right\} \tag{4}$$

The parameters in Eqn (4) were determined for all the curves in Figure 22 by using a regression to minimize the sum of the residuals. (A residual is the difference between the regression fit for the integral worth at a particular control rod position and the calculated/experimentally determined integral worth at that control rod position.) The regression fits for all the curves were produced using the regression package found in the SigmaPlot® software.

A summary of the fit parameters (A, a, and z1) determined in the regression analyses is found in Table 2. The table also contains fit parameters obtained for the integral worth curves for several other reactor configurations that were calculated using the ACRR model.

Table 2. Summary of Regression Fits for Integral Worth Curves

ACRR Configuration	A	a	z_1	Total $\Delta\rho$
Standard Configuration Experiment	-0.0036123	0.00043227	-1030.7285	$12.80
IP Configuration Experiment	-0.0031716	0.00043565	-1088.8707	$11.14 $11.35*
Empty Central Cavity	-0.0034172	0.00044684	-1056.8455	$11.73
Worth Curve Fits for Other Reactor Configurations				
32” Pedestal in the Central Cavity	-0.0032793	0.00041871	-1354.0190	$11.80
32” + 8” Pedestals in the Central Cavity	-0.0033594	0.00042564	-1302.4721	$11.94
Aluminum Dosimetry Bucket on 32” + 8” Pedestals in the Central Cavity	-0.0033362	0.00042548	-1256.9635	$11.89
Pb-B_4C Spectrum Modifying Bucket on 32” Pedestal in the Central Cavity	-0.0038145	0.00043986	-1084.6202	$13.28
Pb-B_4C Spectrum Modifying Bucket on 32” + 8” Pedestals in the Central Cavity	-0.0037058	0.00041366	-1393.5259	$13.47
LP-1 Spectrum Modifying Bucket on 32” Pedestal in the Central Cavity	-0.0033824	0.00042940	-1191.8717	$11.99
Neutron Generator Boom Box on 32” Pedestal in the Central Cavity	-0.0033059	0.00043806	-1121.8804	$11.54
The value of z_0 corresponds to the length of travel of the control rods (i.e., z_0 = 5500). *A control rod drop was performed, but the value was not included in the regression fit.				

An examination of the data points and curves in Figure 22 and the regression fits in Table 2 reveal significant differences between the model calculations and the experimental determinations of the integral worth. In an effort to quantify these differences, a Δ between the model and experiment is calculated. The Δ’s were calculated as a function of z (i.e., control rod bank position) for the regression fits. The differences were obtained by subtracting the value (regression fit) of the integral worth of the model calculation from the value determined by the experiments. Thus, the Δ’s are obtained by using Eqn (5):

$$\Delta(z) = \rho(z, MCNPX) - \rho(z, Experiment) \quad (5).$$

The differences between the ACRR control calibrations and the model calculation are found in Figure 23. The figure shows that the Δ for the model and standard configuration is constant (at ~-$1.08) between 0 and 2250 control rod units. The constant Δ indicates that the slope of the regression fits are approximately the same in this region of the integral worth curves. This also demonstrates that the differences between the model and standard configuration integral worth curves are found in the upper region (>2250 rod units) of the control rod bank. This observation will be relevant when predictions of the experiment package differential worth require moving the control rod bank to positions higher than 2250 rod units.

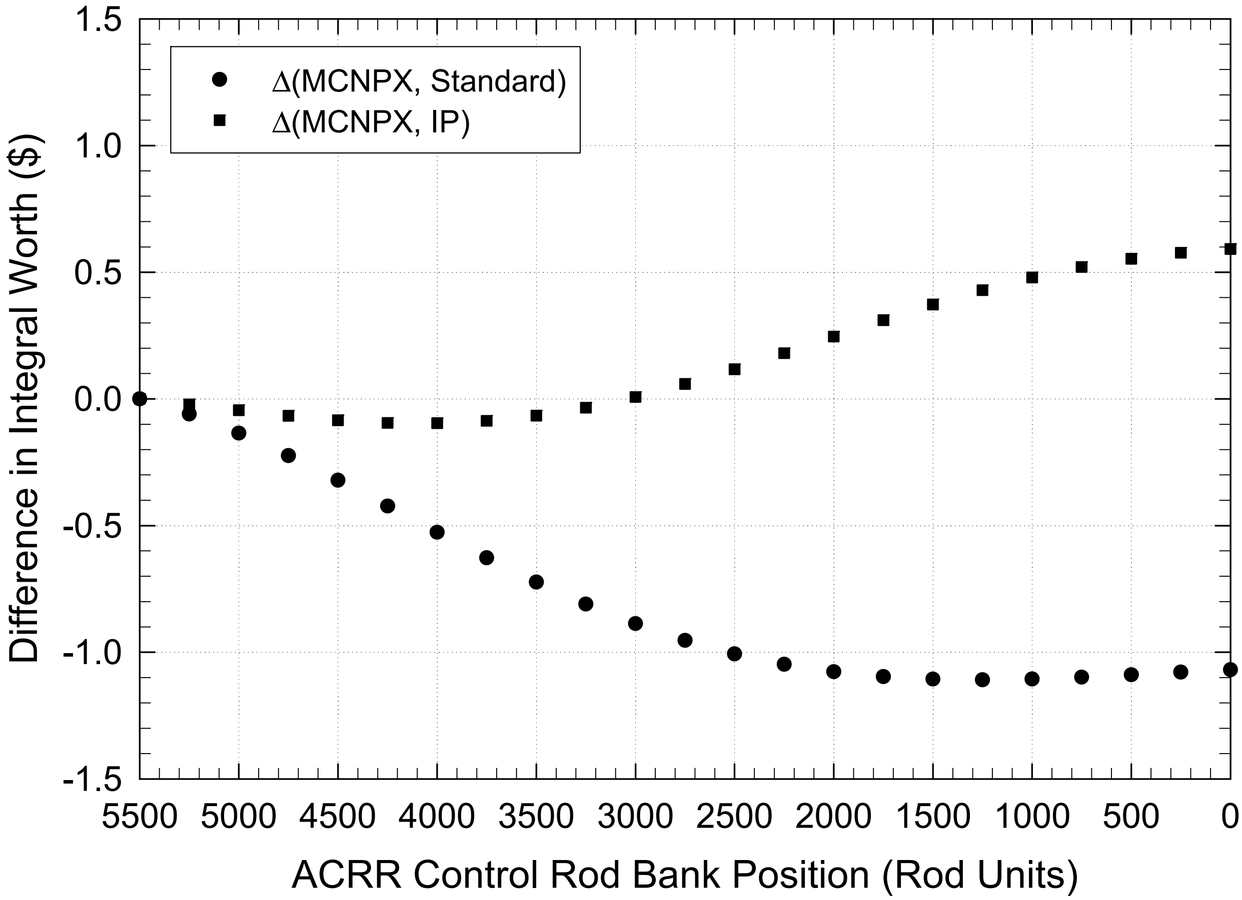

Figure 23. Experiment/Model Difference in Integral Worth

Currently, the MCNP model of the ACRR is used to make estimates of the differential reactivity worth of experiment packages (see Chapter 5 for the procedure used for this estimation). The difference between the standard configuration and the model for bank positions greater than 2250 is not constant. Figure 23 above indicates that the differential worth large negative reactivity worth packages will be over-estimated (i.e., predictions will be more negative than measurements). Using the data for the standard configuration, a linear fit for the difference in integral worth in the region between 2250 and 5500 rod units was performed. This linear fit can be used to adjust the reactivity worth prediction for packages that require movement of the control rod bank to position greater than 2250 rod units. The adjustment of the reactivity worth estimates will use Eqn (6):

$$
\begin{aligned}
&Adj = 0 && [0 \le z \le 2250] \\
&Adj = (0.00033886z - 1.8634) + 1.085 && [2250 \le z \le 5500]
\end{aligned} \qquad (6)
$$

where *Adj* is the adjustment to the reactivity worth estimate in dollars and z is in rod units. A plot of the adjustment along with the data points used for the linear fit is found in Figure 24. The figure also contains an example adjustment performed at 3500 rod units.

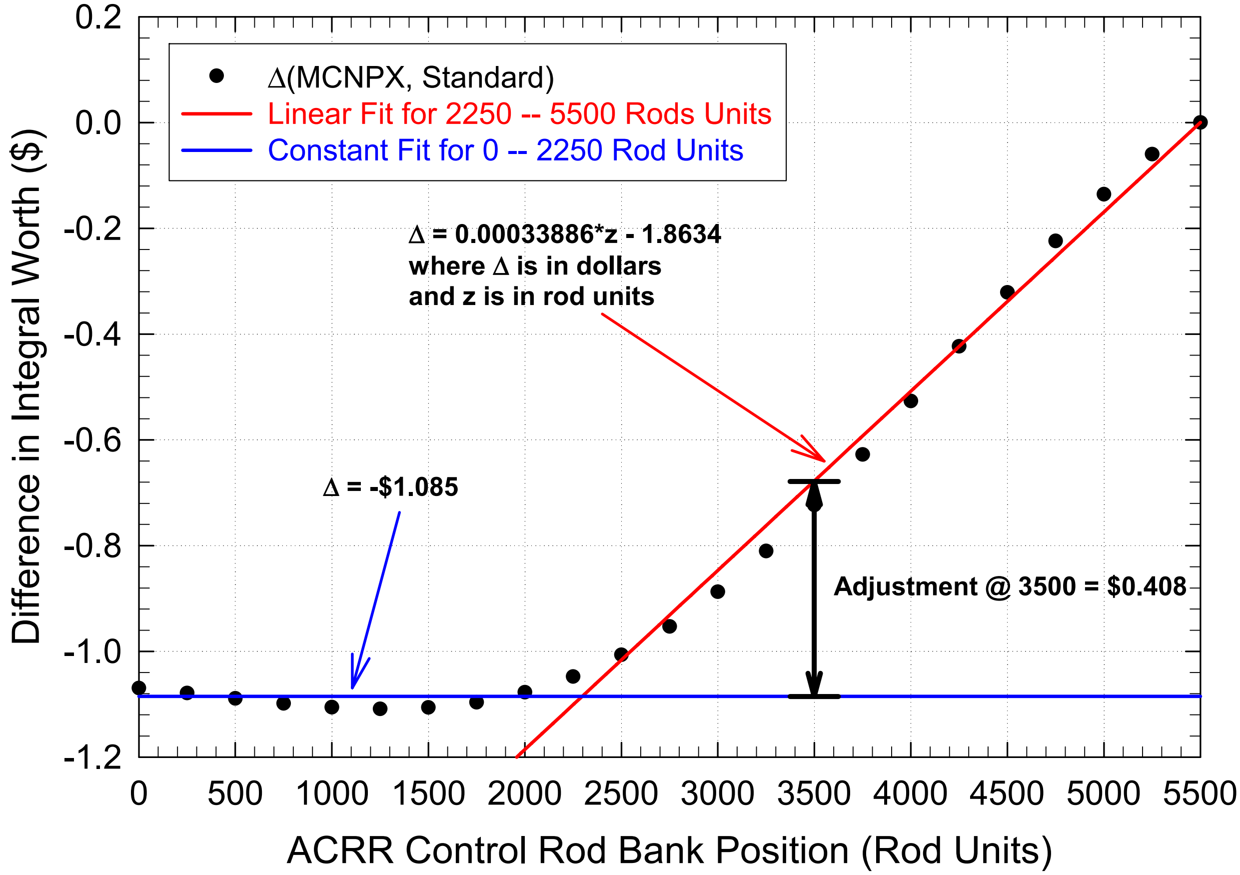

Figure 24. Reactivity Worth Estimate Adjustment Fit

4. DELAYED CRITICAL POSITION COMPARISONS

4.1. Calculated Delayed Critical Positions

Using the calculated values of k_{eff} for that were generated for each of the reactor configurations, a delayed critical (k_{eff} = 1.0000) position for the reactor model can be calculated (or estimated). Due to the Monte Carlo statistical nature of the k_{eff} estimate produced by MCNP, there is some uncertainty in the control rod position for delayed criticality in the model.

To account for the statistical uncertainties in the k_{eff} estimates, an average of several values of k_{eff} around the delayed critical location was taken. An average of 11 values for k_{eff} (representing 100 rod units) was calculated by locating the region where k_{eff} oscillated between 0.999 and 1.001 and using the values of k_{eff} for the average. The results of the delayed critical position determinations are found below in Table 3. It should be noted that 1 rod unit is equal to 0.01 cm. Thus, the average over 100 rod units represents a movement of the control rod of 1 cm. In addition, the uncertainty in the rod units in the table represents 0.33-0.34 cm. The delayed critical positions indicated in Table 3 are all "Up DC" control rod positions. An "Up DC" is the control rod position for delayed neutron criticality in the ACRR with the transient rods in the "full up" (poison section completely out of the reactor) configuration.

Table 3. Calculated Delayed Critical Positions

ACRR Configuration	Average k_{eff}	σ_{keff}	Rod Units*
Empty Central Cavity	0.999935	0.001217	1490
32" Pedestal in the Central Cavity	1.000146	0.001313	1350
32" + 8" Pedestals in the Central Cavity	0.999954	0.001086	1260
Aluminum Dosimetry Bucket on 32" + 8" Pedestals in the Central Cavity	0.999907	0.001128	1320
Pb-B_4C Spectrum Modifying Bucket on 32" Pedestal in the Central Cavity	1.000085	0.000901	3340
Pb-B_4C Spectrum Modifying Bucket on 32" + 8" Pedestals in the Central Cavity	0.999998	0.001307	3190
LP-1 Spectrum Modifying Bucket on 32" Pedestal in the Central Cavity	1.000020	0.001271	2220
Neutron Generator Boom Box on 32" Pedestal in the Central Cavity	1.000971	0.001309	1070
*The 1σ error in the number of rod units is 33 to 34 rod units for each configuration.			

4.2. Measured Delayed Critical Positions

During an experiment series at the ACRR, the delayed critical position for various reactor configurations was determined. The control rod positions (in rod units) for the measured delayed criticality for these configurations are found in Table 4 along with the date that the measurement was taken. The measured values include an "Up DC" position and a "Down DC" position. The "Up DC" is defined above while a "Down DC" is the control rod position for delayed neutron criticality in the ACRR with the transient rods in the "full down" (poison section completely in the reactor) configuration. (NOTE: The measured delayed critical position will vary based on ACRR pool temperature, fuel temperature, power history, etc.)

Table 4. Measured Delayed Critical Positions

ACRR Configuration	Up Delayed Critical Position[1] (Rod Units and Date)	Down Delayed Critical Position[2] (Rod Units and Date)
32" Pedestal in the Central Cavity	1527 (03/03/04)	2414 (03/03/04)
32" + 8" Pedestals in the Central Cavity	1458 (03/01/04)	2371 (03/01/04)
Pb-B_4C Spectrum Modifying Bucket on 32" Pedestal in the Central Cavity	3205 (03/09/04)	4426 (03/09/04)
LP-1 Spectrum Modifying Bucket on 32" Pedestal in the Central Cavity	2306 (03/11/04)	3128 (03/11/04)
Neutron Generator Boom Box on 32" Pedestal in the Central Cavity	1306 (03/10/04)	2259 (03/10/04)
[1]This is the control rod position for delayed neutron criticality (k_{eff} = 1.0000) in the ACRR with the transient rods in the "full up" configuration. [2]This is the control rod position for delayed neutron criticality in the ACRR with the transient rods in the "full down" configuration.		

4.3. Difference Between Delayed Critical Positions

A comparison of the calculated "Up DC" control rod positions (see Table 3) with the measured control rod positions (see Table 4) for the same reactor configurations is found in Table 5. In every reactor configuration found in the table, the difference between the calculation and measurement is less than an inch (2.54 cm).

Table 5. Difference in Delayed Critical Positions

ACRR Configuration	Δ in Rod Units	Δ in Centimeters
32" Pedestal in the Central Cavity	177	1.77
32" + 8" Pedestals in the Central Cavity	198	1.98
Pb-B_4C Spectrum Modifying Bucket on 32" Pedestal in the Central Cavity	-135	-1.35
LP-1 Spectrum Modifying Bucket on 32" Pedestal in the Central Cavity	86	0.86
Neutron Generator Boom Box on 32" Pedestal in the Central Cavity	236	2.36
Δ is calculated by (Measured Rod Units – Calculated Rod Units).		

To quantify this difference between the model calculations and measurements in another manner, the measured delayed critical positions in Table 4 were used for the control rod (and transient rod) positions in the model. The calculated k_{eff} values for the configurations measured in Table 4 are found in Table 6. Table 6 also contains a difference in the reactivity ($\Delta\rho$) between the model and experiment. The $\Delta\rho$ calculation was performed using Eqn (7) assuming that the measurement produces a k_{meas} = 1.0000:

$$\Delta\rho = \frac{(k_{eff} - k_{meas})}{k_{eff} \cdot k_{meas}} \cdot \frac{1}{\beta_{eff}} \tag{7}$$

where β_{eff} is 0.0073 (historic value for the ACRR).

Table 6. Calculated k_{eff} for Various Configurations

ACRR Configuration	Control Rod Position in Model	Calculated k_{eff}	$\Delta\rho$[1] for Model Comparison
Up DC[2] for 32" Pedestal in the Central Cavity	-39.731	1.00299 +/- 0.00020	$0.410
Down DC for 32" Pedestal in the Central Cavity	-30.851	0.99424 +/- 0.00020	-$0.789
Up DC for 32" + 8" Pedestals in the Central Cavity	-40.421	1.00340 +/- 0.00020	$0.466
Down DC for 32" + 8" Pedestals in the Central Cavity	-31.291	0.99439 +/- 0.00021	-$0.768
Up DC for Pb-B_4C Spectrum Modifying Bucket on 32" Pedestal	-22.951	0.99681 +/- 0.00020	-$0.437
Down DC for Pb-B_4C Spectrum Modifying Bucket on 32" Pedestal	-10.741	0.98964 +/- 0.00020	-$1.419
Up DC for LP-1 Spectrum Modifying Bucket on 32" Pedestal	-31.941	1.00246 +/- 0.00019	$0.337
Down DC for LP-1 Spectrum Modifying Bucket on 32" Pedestal	-23.721	0.99382 +/- 0.00020	-$0.847
Up DC for Empty NG Boom Box on 32" Pedestal	-41.941	1.00449 +/- 0.00021	$0.615
Down DC for Empty NG Boom Box on 32" Pedestal	-32.411	0.99579 +/- 0.00020	-$0.578

[1]$\Delta\rho$ is the difference in reactivity worth between the model and measurement (β_{eff} = 0.0073 for ACRR).
[2]DC is delayed neutron criticality (k_{eff} = 1.0000).

An examination of the "Up DC" configurations in Table 6 reveals an average $\Delta\rho$ of $0.278 +/- 0.4126. If the Pb-B_4C spectrum modifying bucket is excluded from the average (as an outlier), the average $\Delta\rho$ is $0.457 +/- 0.118. The "Down DC" configurations in Table 6 produce an average $\Delta\rho$ of -$0.880 +/- 0.318.

5. SAMPLE EXPERIMENT WORTH CALCULATIONS

5.1. Methodology for Estimating Experiment Package Worth

As mentioned in the description of the ACRR model, there is a section in the model that is designated for experiment packages. The following outlines the methodology used to estimate an experiment package worth:

1. The experiment package model is created external to the ACRR. The modeler should be careful to include a transformation card (TR6) for each surface (surfaces should be numbered starting at surface 1000) used to construct the model. The geometry should be tested before placing the package in the ACRR model.
2. The newly created experiment package is placed in the ACRR model, and the geometry is tested.
3. An initial guess at the proper location for the control rod bank is made. The control rods in the ACRR model are moved to that location.
4. Calculate k_{eff} for the experiment package in the ACRR with the control rod bank in the "guessed" located.
5. After the calculation is complete, determine if the control rod bank needs to be moved to make k_{eff} closer to 1.00000. If it is not, make another guess at the control rod bank location.
6. Perform 4 and 5 until the analyst is satisfied with the value of k_{eff}.
7. When k_{eff} is close enough to 1.00000 (close enough in this context means that k_{eff} = 1.00000 is in the 95% confidence interval [i.e., within 2σ]), then remove the experiment package and calculate k_{eff} without moving the control rod bank.

When the above process is complete, the analyst will have k_{eff} for 2 cases in the ACRR (with and without the experiment package). Using the definition of reactivity (see Eqn (1) above), we can compute the difference in reactivity between the 2 cases. This is done by using Eqn (8):

$$\Delta\rho[Experiment] = \frac{(k_2 - k_1)}{k_2 \cdot k_1} \cdot \frac{1}{\beta_{eff}} \qquad (8).$$

Now, each of the 2 k_{eff} values will have Monte Carlo statistical variation. These variations are reported by MCNP as 1σ values. In order to place the statistical error on the estimated package worth, the error propagation method outlined in [Kn89] is used. To properly apply this error propagation technique, the transformation in Eqn (9) is used:

$$u = \frac{(k_2 - k_1)}{k_2 \cdot k_1} \qquad (9).$$

The error propagation technique can now be used. The statistical error (variance) for the estimated package worth is calculated by using the transformation above and Eqn (10):

$$\sigma_u^2 = \left(\frac{\partial u}{\partial k_1}\right)^2 \cdot \sigma_{k_1}^2 + \left(\frac{\partial u}{\partial k_2}\right)^2 \cdot \sigma_{k_2}^2 \qquad (10).$$

Once the differentiations in Eqn (10) are performed, the standard deviation for estimated package worth can be calculated. The result of the calculation for the standard deviation of the package worth is found in Eqn (11):

$$\sigma_{\Delta\rho} = \sqrt{\left(\frac{\sigma_{k_2}^2}{k_2^4} + \frac{\sigma_{k_1}^2}{k_1^4}\right)} \cdot \frac{1}{\beta_{eff}} \qquad (11).$$

5.2. Spectrum Modifying Buckets

Two central cavity inserts designed to modify the neutron/gamma ratio and neutron spectrum in the cavity are included in the model. The critical position for each of the spectrum modifying buckets was determined using the process described above. The results of the process are found in Table 7.

Table 7. k_{eff} for Worth Estimates of Spectrum Modifying Buckets

MCNP Run Information	k_{eff}	σ for k_{eff}
Pb-B_4C Spectrum Modifying Bucket		
ACRR with Pb-B_4C Spectrum Modifying Bucket on 32” Pedestal (CR = 3290 Rod Units)	0.99983	0.00072
ACRR with 32” Pedestal (CR = 3290 Rod Units)	1.04791	0.00075
LP-1 Spectrum Modifying Bucket		
ACRR with LP-1 Spectrum Modifying Bucket on 32” Pedestal (CR = 2160 Rod Units)	0.99973	0.00068
ACRR with 32” Pedestal (CR = 2160 Rod Units)	1.01959	0.00073

Using the values for calculated for k_{eff} in Table 7, the estimated reactivity worth of the spectrum modifying buckets was calculated. Those calculated reactivity values are found in Table 8 along with the values measured at the ACRR. The difference between the two (calculated and measured) is calculated and found in the table as Δ. The Pb-B_4C spectrum modifying bucket requires control rod bank movement greater than 2250 rod units. The adjustment of the reactivity worth estimate (described in Chapter 3) was applied to the Pb-B_4C spectrum modifying bucket. The result of the adjustment is also found in Table 8.

Table 8. Package Worth for Spectrum Modifying Buckets

ACRR Run Number	Measured Bucket Worth	Calculated Bucket Worth	Δ
$Pb\text{-}B_4C$ Spectrum Modifying Bucket			
8002	-$5.82	-$6.29 +/- 0.14 Adjusted*: -$5.95	-$0.47 -$0.13
LP-1 Spectrum Modifying Bucket			
8025	-$2.59	-$2.67 +/- 0.13	-$0.08
***The adjustment at z = 3290 rod units is $0.336.**			

5.3. Neutron Generator (NG) Boom Box

The boom box for neutron generator testing has been modeled. Many experiments have been performed at the ACRR using this test environment. Two calculations are required to estimate the reactivity worth of this "experiment package." The calculation descriptions and results of those calculations are found below in Table 9.

Table 9: k_{eff} for Worth Estimates of NG Boom Box

MCNP Run Information	k_{eff}	σ for k_{eff}
ACRR with Neutron Generator Boom Box on 32" Pedestal (CR = 1010 Rod Units)	0.99955	0.00070
ACRR with 32" Pedestal (CR = 1010 Rod Units)	0.99310	0.00077

Using the values for calculated for k_{eff} in Table 9, the estimated reactivity worth of the neutron generator boom box was calculated. The calculated reactivity estimate is found in Table 10 along with the value measured at the ACRR. The difference between the two (calculated and measured) is calculated and found in the table as Δ.

Table 10: Package Worth for NG Boom Box

ACRR Run Number	Measured Box Worth	Calculated Box Worth	Δ
8024	$0.61	$0.70 +/- 0.11	$0.09

5.4. Radiation Effects Sciences (RES) Validation Sphere Experiments

A series of RES experiments were performed for NuGET code validation. The experiment series used four different sphere configurations (4" and 7" high-density polyethylene [HDPE] and 4" and 7" aluminum [Al6061]) in two different reactor environments (ACRR-Central Cavity and the $Pb\text{-}B_4C$ spectrum modifying bucket). The twelve calculation descriptions and results used to estimate the reactivity worth of each of the sphere/environment combinations are found in Table 11.

Table 11: k_{eff} for Worth Estimates of RES Validation Spheres

MCNP Run Information	k_{eff}	σ for k_{eff}
4” Diameter High-Density Polyethylene (HDPE) Sphere		
ACRR with Aluminum Bucket on 32” + 8” Pedestals and a 4” Diameter HDPE Sphere (CR = 1510 Rod Units)	0.99926	0.00075
ACRR with Aluminum Bucket on 32” + 8” Pedestals (CR = 1510 Rod Units)	1.00354	0.00078
7” Diameter HDPE Sphere		
ACRR with Aluminum Bucket on 32” + 8” Pedestals and a 7” Diameter HDPE Sphere (CR = 2000 Rod Units)	1.00006	0.00073
ACRR with Aluminum Bucket on 32” + 8” Pedestals (CR = 2000 Rod Units)	1.02122	0.00073
4” Diameter Aluminum (Al6061) Sphere		
ACRR with Aluminum Bucket on 32” + 8” Pedestals and a 4” Diameter Al6061 Sphere (CR = 1345 Rod Units)	0.99970	0.00073
ACRR with Aluminum Bucket on 32” + 8” Pedestals (CR = 1345 Rod Units)	1.00146	0.00074
7” Diameter Al6061 Sphere		
ACRR with Aluminum Bucket on 32” + 8” Pedestals and a 7” Diameter Al6061 Sphere (CR = 1450 Rod Units)	1.00006	0.00073
ACRR with Aluminum Bucket on 32” + 8” Pedestals (CR = 1450 Rod Units)	1.00244	0.00074
4” Diameter HDPE Sphere in Pb-B_4C Bucket		
ACRR with Pb-B_4C Spectrum Modifying Bucket on 32” Pedestal and a 4” Diameter HDPE Sphere (CR = 3575 Rod Units)	0.99980	0.00075
ACRR with 32” Pedestal (CR = 3575 Rod Units)	1.05402	0.00078
4” Diameter Al6061 Sphere in Pb-B_4C Bucket		
ACRR with Pb-B_4C Spectrum Modifying Bucket on 32” Pedestal and a 4” Diameter Al6061 Sphere (CR = 3320 Rod Units)	1.00011	0.00072
ACRR with 32” Pedestal (CR = 3320 Rod Units)	1.04773	0.00076

Using the values for calculated for k_{eff} in Table 11, the estimated reactivity worth of the RES validation spheres was calculated. Those calculated reactivity values are found in Table 12 along with the values measured at the ACRR. The difference between the two (calculated and measured) is calculated and found in the table as Δ. The Pb-B_4C spectrum modifying bucket environments required control rod bank movements greater than 2250 rod units. The adjustments of the reactivity worth estimates (described in Chapter 3) were applied to the Pb-B_4C spectrum modifying bucket calculations. The results of the adjustments are also found in Table 12.

Table 12: Package Worth for RES Validation Spheres

ACRR Run Numbers	Measured Sphere Worth	Calculated Sphere Worth	Δ
4" Diameter HDPE Sphere			
7726 7740 7753 7803 7837	-\$0.67 +/- 0.05	-\$0.59 +/- 0.15	\$0.08
7" Diameter HDPE Sphere			
7654 7670 7679 7728 7742	-\$2.83 +/- 0.07	-\$2.84 +/- 0.14	-\$0.01
4" Diameter Al6061 Sphere			
7727 7741 7765 7832 7838	-\$0.11 +/- 0.03	-\$0.24 +/- 0.14	-\$0.13
7" Diameter Al6061 Sphere			
7655 7671 7680 7729 7743	-\$0.37 +/- 0.06	-\$0.33 +/- 0.14	\$0.04
4" Diameter HDPE Sphere in Pb-B_4C Bucket			
8001	-\$6.55	-\$7.05 +/- 0.14 Adjusted*: -\$6.62	-\$0.50 -\$0.07
4" Diameter Al6061 Sphere in Pb-B_4C Bucket			
8003	-\$5.83	-\$6.23 +/- 0.14 Adjusted^: -\$5.88	-\$0.40 -\$0.05
***The adjustment at z = 3575 rod units is \$0.433.** **^The adjustment at z = 3320 rod units is \$0.347.**			

To summarize, the differential reactivity worth was estimated and compared to measurements for nine experiment packages. Three of the packages required movement of the control rod bank greater than 2250 rod units. The adjustment described in Chapter 3 was applied to the estimated reactivity of those three packages. The average of the difference between the measurement and calculation for the nine unadjusted package reactivity worth estimates is -\$0.153 +/- 0.239. The average of the absolute deviation |Δ| for the unadjusted package reactivity worth estimates is

\$0.200 +/- 0.197. The average of the difference between the measurement and calculation for the adjusted package reactivity worth estimates is -\$0.029 +/- 0.084. The average of the absolute deviation $|\Delta|$ for the adjusted package reactivity worth estimates is \$0.076 +/- 0.039.

Although this series of comparisons shows excellent agreement, the results found here may not be typical. For experiment packages that are more complicated than these examples, the differences may be much greater than the ~\$0.08 seen above in the adjusted reactivity worth estimates. A more realistic value for the total uncertainty associated with any particular reactivity worth estimate is +/-\$0.50. (*NOTE: The uncertainties for the calculated worth estimates in Tables 8, 10, and 12 represent ONLY the Monte Carlo statistical uncertainty calculated using Eqn (11)*).

6. PARTICLE SPECTRA

6.1. ACRR-Central Cavity Neutron Spectrum

The neutron spectrum found in the "empty" ACRR-Central Cavity has been determined by the SNL-Radiation Metrology Laboratory (SNLRML) using spectrum unfold techniques [Gr94]. The "empty" configuration is the central cavity with an aluminum experiment bucket with the SNLRML dosimetry fixture inside sitting on top of the 32" + 8" pedestals. The central cavity spectrum produced by the SNLRML is known as ACF9.

A calculation of the neutron spectrum in the model of the ACRR was performed. The model used the aluminum dosimetry bucket sitting on top of the 32" + 8" pedestals. The SNLRML dosimetry fixture was not modeled. Instead, a 4" diameter sphere located at the fuel centerline was used to score the neutron spectrum. A comparison of the normalized neutron fluence in the ACRR-Central Cavity is found in Figure 25.

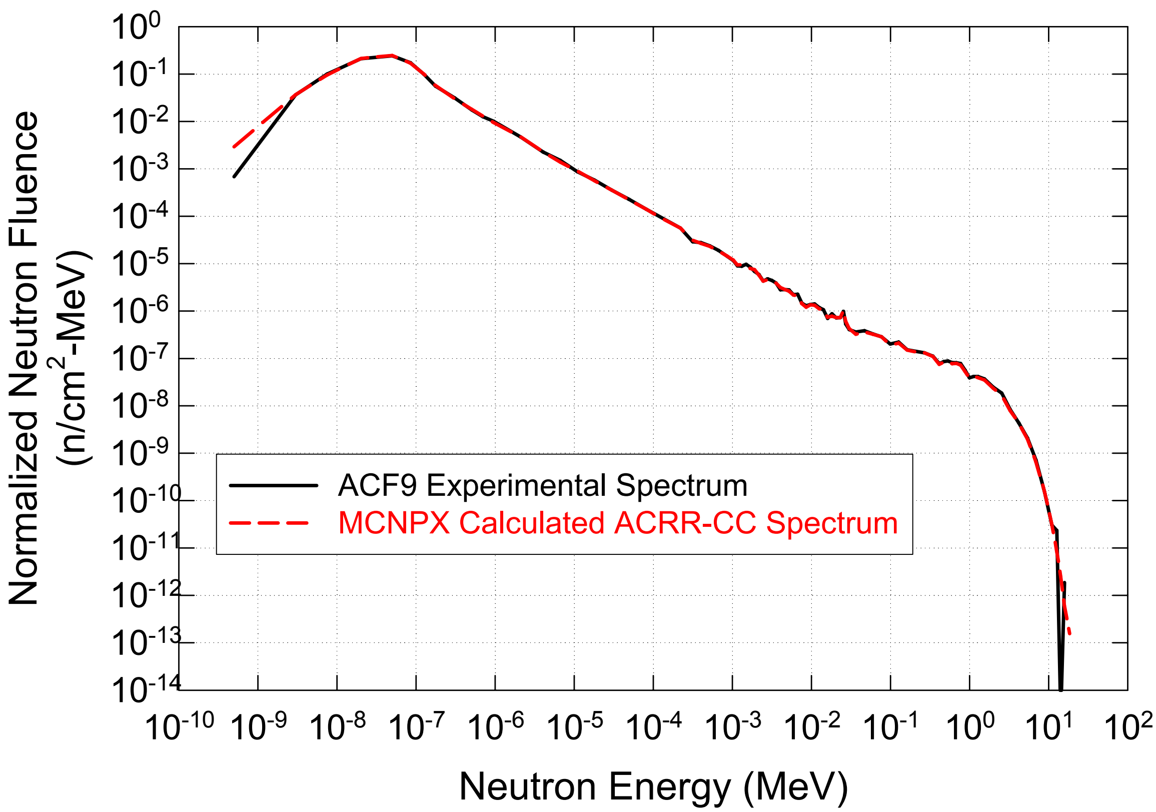

Figure 25. Comparison of ACRR-Central Cavity Neutron Spectra

The log-log scale used in Figure 25 makes it difficult to compare in a reasonable manner. In order to make the comparison easier, the ratio of the calculated spectrum to the ACF9 spectrum is found in Figure 26. Points that are not seen in Figure 26 are found at 5.0 x 10^{-10} MeV and 14.2 MeV. These are outside the scale of the figure, but the Monte Carlo statistics of those energy groups indicate that the values for the calculations are unreliable (i.e., the relative error is greater than 0.10 for those energy groups). Examining the ratios in the figure, we find that the vast majority of the energy groups are within 15% (or 0.85-1.15) of the determined spectrum. In fact, 85 out of 89 groups (~96%) are in this range. Thus, the central cavity neutron spectrum calculated by the MCNP model agrees quite well with the environment determined by spectrum unfold techniques.

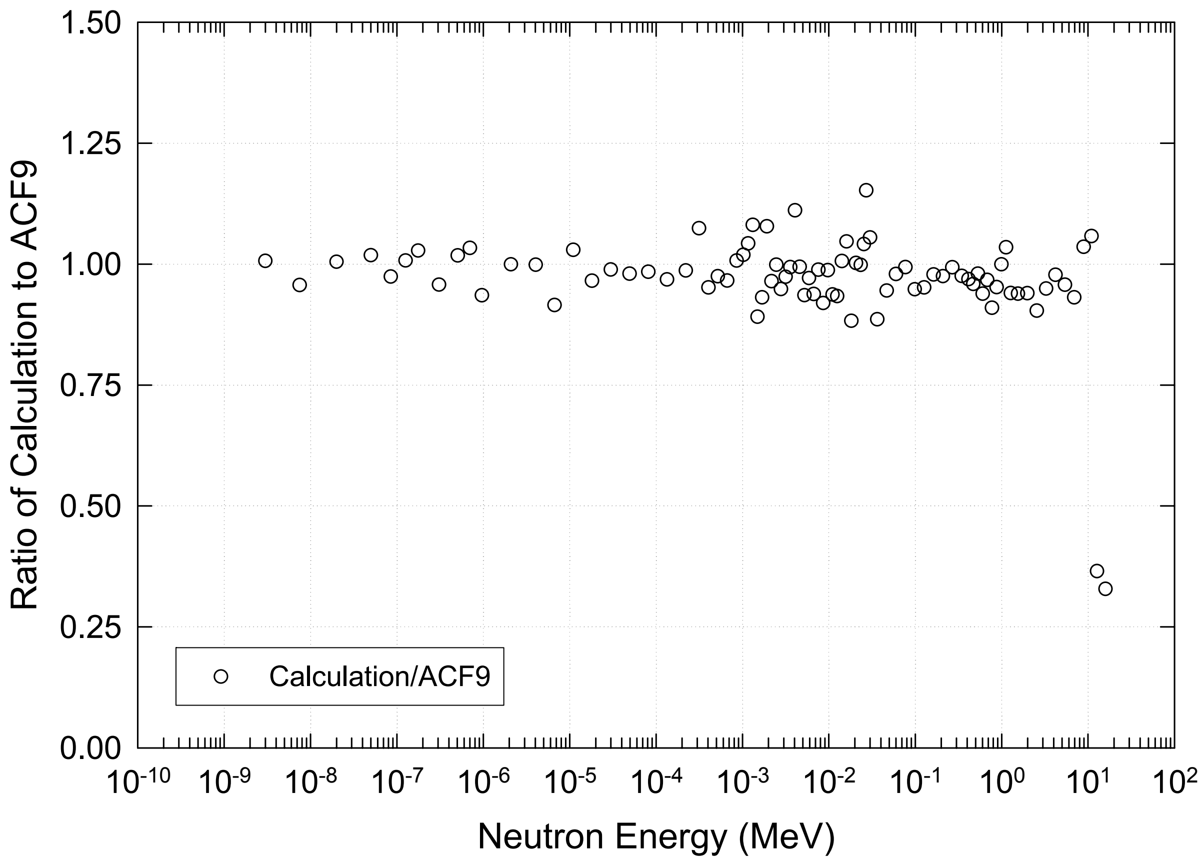

Figure 26. Ratio of Calculated ACRR-CC Spectrum to ACF9

6.2. Pb-B_4C Spectrum-Modifying Bucket Neutron Spectrum

The neutron spectrum found in the Pb-B_4C spectrum-modifying bucket was also determined by the SNLRML using spectrum unfold techniques [Gr94]. This configuration is the Pb-B_4C spectrum-modifying bucket on the 32” + 8” pedestals with a SNLRML dosimetry fixture inside. The Pb-B_4C spectrum produced by the SNLRML is known as TPB13.

A calculation of the neutron spectrum in the model of the ACRR was performed. The model used the Pb-B_4C spectrum-modifying bucket on top of the 32” pedestal. The SNLRML dosimetry fixture was not modeled. Instead, a 4” diameter sphere located at the fuel centerline was used to score the neutron spectrum. A comparison of the normalized neutron fluence in the Pb-B_4C spectrum modifying bucket is found in Figure 27.

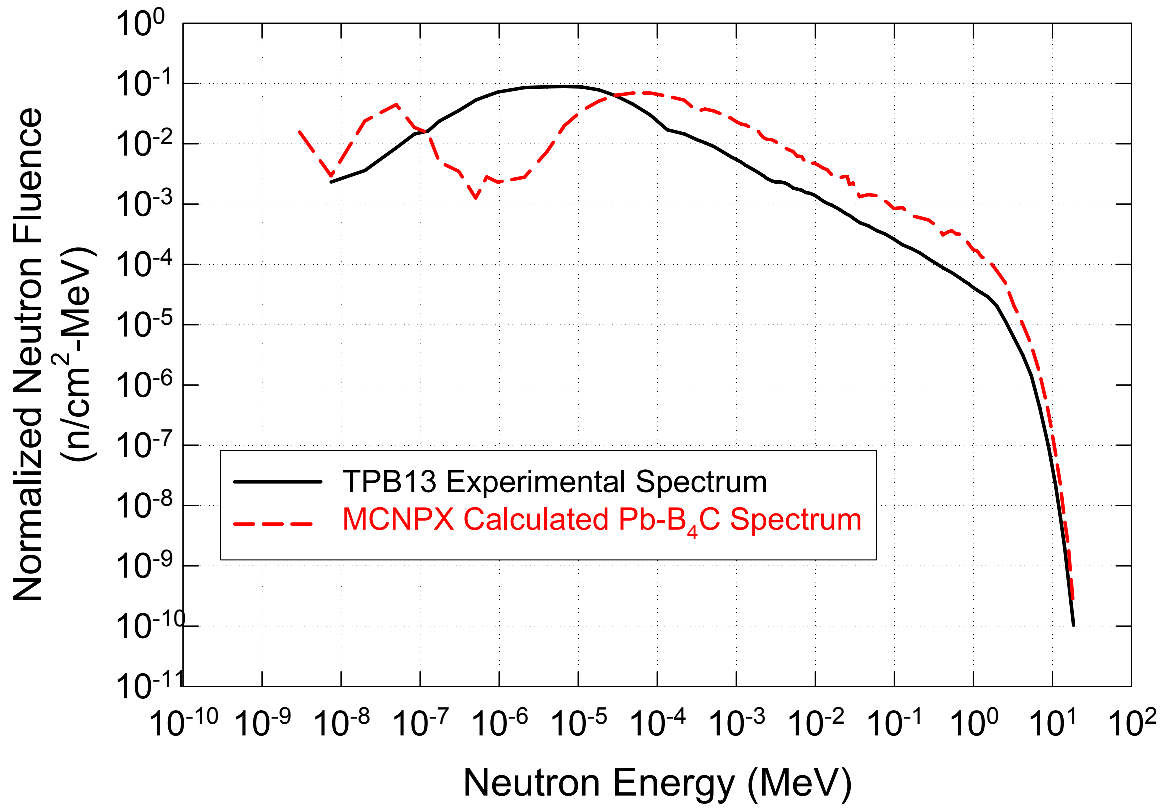

Figure 27. Comparison of Pb-B_4C Bucket Neutron Spectra

Although the fluences in Figure 27 are displayed on a log-log scale, it is quite obvious in the figure that there is significant disagreement between the calculation and the “measured” spectrum. Since the spectra are normalized, the disagreement in the low energy portion of the spectra distorts the agreement at the upper energies. NuGET code validation calculations comparing the calculated activities for nickel foils and sulfur tablets (neutron spectrum monitors with thresholds above 1.0 MeV) have calculation to experiment (C/E) ratios between 0.90-1.10 (see references [De04-1] and [De04-2]). Thus, there is excellent agreement for the higher energy portion of the neutron spectrum in the Pb-B_4C spectrum modifying bucket. However, the same validation calculations show large disagreements for thermal neutron monitors.

6.3. Calculated Gamma Spectra

The photon spectra in various reactor environments at the ACRR are currently unable to be measured due to the high ionizing dose rates. These high gamma dose rates in the reactor are often the reason the ACRR is chosen for a given experiment. The MCNP model of the ACRR provides the best available estimates of the gamma spectra in the various environments. Normalized photon spectra for the ACRR-Central Cavity and the Pb-B_4C spectrum-modifying bucket are found in Figure 28.

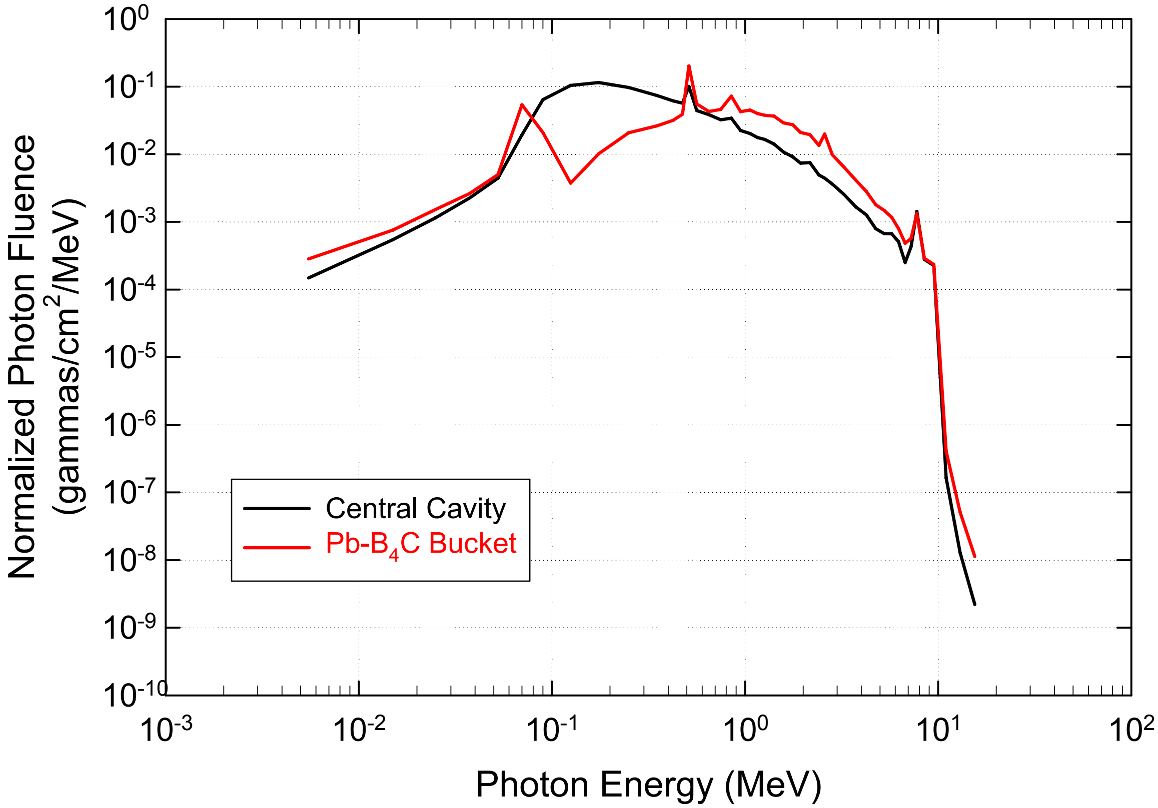

Figure 28. Calculated ACRR Photon Spectra

It is quite obvious that the gamma spectra calculated for the environments found in Figure 28 are different. Calculations and experimental measurements of the photon doses (on a per reactor MJ basis) in the Pb-B_4C bucket are ~80% lower than the photon doses in the ACRR-Central Cavity (see reference [De04-3]).

7. CONCLUSIONS

Integral reactivity worth curves for the ACRR control rod bank were calculated for several reactor configurations. These integral reactivity worth curves (both measured and calculated) are fit to a functional form that corresponds to the results of perturbation theory. The total control rod bank worth differs by ~$1.08 between the MCNP model and the standard (pulse) configuration of the ACRR. However, the difference between the model and the measured worth curves is constant for control rod bank movements less than 2250 rod units. A linear fit to the difference for movements greater than 2250 rod units allows an adjustment in the estimates of experiment package reactivity worth.

The differential reactivity worth was estimated and compared to measurements for nine experiment packages. Three of the packages required movement of the control rod bank greater than 2250 rod units. The adjustment described above was applied to the estimated reactivity of those three packages. The average of the difference between the measurement and calculation for the nine unadjusted package reactivity worth estimates is -$0.153 +/- 0.239. The average of the absolute deviation for the unadjusted package reactivity worth estimates is $0.200 +/- 0.197. The average of the difference between the measurement and calculation for the adjusted package reactivity worth estimates is -$0.029 +/- 0.084. The average of the absolute deviation for the adjusted package reactivity worth estimates is $0.076 +/- 0.039. Although this series of comparisons shows excellent agreement, the results found here may not be typical. For experiment packages that are more complicated than these examples, the differences may be much greater than the ~$0.08 seen above in the adjusted reactivity worth estimates. A more realistic value for the total uncertainty associated with any particular reactivity worth estimate is +/-$0.50.

The neutron spectra for two different reactor environments (ACRR-CC and the Pb-B_4C spectrum-modifying bucket) were calculated and were compared to experimental neutron spectra determined by spectrum unfolding techniques using activation foils. The spectrum calculated for the ACRR-Central Cavity agrees quite well with the experimentally determined ACF9 spectrum. In fact, 85 out of the 89 neutron energy groups (~96%) are within 15% agreement. However, the thermal portion of the calculated Pb-B_4C spectrum-modifying bucket spectrum disagrees drastically with the experimentally determined TPB13 spectrum.

The photon spectra in various reactor environments at the ACRR are currently unable to be measured due to the high ionizing dose rates. These high gamma dose rates in the reactor are often the reason the ACRR is chosen for a given experiment. The MCNP model of the ACRR provides the best available estimates of the gamma spectra in the various environments. The gamma spectra for two different reactor environments (ACRR-CC and the Pb-B_4C spectrum-modifying bucket) were calculated and displayed.

The MCNP model presented in this report allows experimenters to more fully understand the test environments for many of the reactor configurations available at the ACRR. Additionally, a standard method for estimating the reactivity worth of experiment packages has been outlined and demonstrated. The demonstrations of this estimation method show that the model provides an excellent platform for estimating reactivity worth of these test objects.

7.1. Future Work

The differences between the model and measured control rod bank worth for rod bank withdrawals greater than 2250 rod units should be investigated in future analytical studies. The technique used to measure the control rod bank worth results in a different "reactor" for each of the measurements. The technique adds a fuel element, moves the control rod bank, and performs a positive period measurement in order to get the differential worth of the control rod bank movement. The nickel reflector elements are not added to the reactor in the approach to critical control rod bank measurements until the all the fuel elements have been added to the reactor. Thus, the deviations seen here are not necessarily unexpected. A series of calculations that matches the reactor configurations used in the "approach to critical" technique may resolve the differences seen in this report.

A transient rod bank worth curve calculation similar to the one performed for the control rod bank should be performed. After the calculation is complete, the results should be compared to the one produced by experiments and found in the ACRR SAR. There is no safety rod bank worth curve in the ACRR SAR. There is only a reference to the total safety rod bank reactivity worth. Thus, a calculation of the total safety rod bank worth would be useful for comparison to the values found in the ACRR SAR.

Finally, several experimenters and reactor operators have noticed that there is sometimes a difference between the reactivity worth of a package during a steady state operation and the reactivity worth of the same package during a pulse operation. This difference may be the result of changing both the axial and radial flux profile (compared to the steady state) during the setup for the pulse operation. A series of experiments that demonstrates this phenomenon should be accurately modeled and calculated using the reactor model described in this report. The calculations should include the package reactivity worth for both steady state and pulse setup, the axial flux profile, and the radial flux profile. It is believed that these comparisons may resolve this long standing "issue" of static versus dynamic package worth.

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8. REFERENCES

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APPENDIX A: MCNP MODEL OF ACRR (FREC-II DECOUPLED)

```
Standard ACRR Model
C
C  Model Developed by R. DePriest (845-8141)
C
C  This model was created using the macrobody feature of MCNP.  Only 1
C    cell (200) has the historical MCNP surface description.  There are
C    spectrum modifying buckets included in the model.
C
C  There will be warnings about surfaces being the same and unused
C   surfaces.  This is a by-product of the macrobodies and the flexibility
C   of using various experiment buckets.
C
C *********************************************************************
C *                           CELL CARDS                              *
C *********************************************************************
C
C  Universe definitions for the standard 236-element core.
C
C     U=1:fuel rods              U=2:water rods
C     U=3:control rods           U=4:safety rods
C     U=5:transient rods         U=6:nickel rods
C     U=7:90% fuel rods          U=9:al rods (empty)
C
C   ********  U=8 is the reactor core fill.  *******
C
C  Regular Fuel Element
C
10  0            -10              U=1  IMP:N,P=1 $Void
11  1   -3.3447   10 -11          U=1  IMP:N,P=1 $UO2-BeO fuel
14  0             11 -14          U=1  IMP:N,P=1 $Void
15  2   -8.4000   14 -15          U=1  IMP:N,P=1 $Niobium
16  0             15 -16          U=1  IMP:N,P=1 $Void Gap
17  4   -2.8000  -17              U=1  IMP:N,P=1 $Lower BeO Plug
18  4   -2.8000  -18              U=1  IMP:N,P=1 $Upper BeO Plug
19  3   -8.0300   17 -19          U=1  IMP:N,P=1 $Lower SS Plug
20  3   -8.0300   18 -20          U=1  IMP:N,P=1 $Upper SS Plug
21  3   -8.0300   19  20  16 -21  U=1  IMP:N,P=1 $SS304
22  5   -1.0000   21 -22          U=1  IMP:N,P=1 $Water
C
C  Water Rods
C
23  5   -1.0000  -22              U=2  IMP:N,P=1 $Water
C
C  Control Rods:  Poison section
C
25  8   -2.4800  -25              U=3  IMP:N,P=1 $B4C poison
26  0             25 -26          U=3  IMP:N,P=1 $Void Cap
27  3   -8.0300   26 -27          U=3  IMP:N,P=1 $Poison sleeve
28  3   -8.0300  -28              U=3  IMP:N,P=1 $Magnaform plug
29  5   -1.0000   27  28 -29      U=3  IMP:N,P=1 $Water
C
C  Control Rods:  Fuel follower
C
30  0            -30              U=3  IMP:N,P=1 $Void
31  1   -3.3447   30 -31          U=3  IMP:N,P=1 $UO2-BeO fuel
32  0             31 -32          U=3  IMP:N,P=1 $Void
33  2   -8.4000   32 -33          U=3  IMP:N,P=1 $Niobium
34  0             33 -34          U=3  IMP:N,P=1 $Void gap
35  4   -2.8000  -35              U=3  IMP:N,P=1 $BeO plug
36  0            -36              U=3  IMP:N,P=1 $Void
37  3   -8.0300   34  35 36 -37   U=3  IMP:N,P=1 $SS304
38  5   -1.0000   37 -38          U=3  IMP:N,P=1 $Water
C
C  Safety Rods:  Poison section
C
39  8   -2.4800  -39              U=4  IMP:N,P=1 $B4C poison
40  0             39 -40          U=4  IMP:N,P=1 $Void cap
41  3   -8.0300   40 -41          U=4  IMP:N,P=1 $Poison sleeve
42  3   -8.0300  -42              U=4  IMP:N,P=1 $Magnaform plug
43  5   -1.0000   41  42 -43      U=4  IMP:N,P=1 $Water
C
C  Safety Rods:  Fuel follower
C
44  0            -44              U=4  IMP:N,P=1 $Void
45  1   -3.3447   44 -45          U=4  IMP:N,P=1 $UO2-BeO fuel
46  0             45 -46          U=4  IMP:N,P=1 $Void
47  2   -8.4000   46 -47          U=4  IMP:N,P=1 $Niobium
```

```
48  0             47 -48          U=4  IMP:N,P=1 $Void gap
49  4   -2.8000   -49             U=4  IMP:N,P=1 $BeO plug
50  0             -50             U=4  IMP:N,P=1 $Void
51  3   -8.0300    48 49  50 -51  U=4  IMP:N,P=1 $SS304
52  5   -1.0000    51 -52         U=4  IMP:N,P=1 $Water
C
C  Transient Rods:  Void section
C
53  0             -53             U=5  IMP:N,P=1 $Void
54  7   -2.7000    53 -54 58 60 61 U=5  IMP:N,P=1 $Al tubing
55  5   -1.0000    54 -55         U=5  IMP:N,P=1 $Water
56  7   -2.7000    55 -56         U=5  IMP:N,P=1 $Al guidex
57  5   -1.0000    56 -57         U=5  IMP:N,P=1 $Water
58  7   -2.7000   -58             U=5  IMP:N,P=1
C
C  Transient Rods:  Poison section
C
59  8   -2.4800   -59             U=5  IMP:N,P=1 $Poison
60  7   -2.7000    59 -60         U=5  IMP:N,P=1 $Inner sleeve
61  0             -61             U=5  IMP:N,P=1 $Void
62  7   -2.7000   -62  54         U=5  IMP:N,P=1 $End plug
C
C  Nickel Rods
C
65  6   -8.9000   -21             U=6  IMP:N,P=1 $Nickel
66  5   -1.0000    21 -22         U=6  IMP:N,P=1 $Water
C
C  90% Fuel Element
C
70  0             -10             U=7  IMP:N,P=1 $Void
71  11  -3.0102    10 -11         U=7  IMP:N,P=1 $UO2-BeO fuel
74  0              11 -14         U=7  IMP:N,P=1 $Void
75  2   -8.4000    14 -15         U=7  IMP:N,P=1 $Niobium
76  0              15 -16         U=7  IMP:N,P=1 $Void Gap
77  4   -2.8000   -17             U=7  IMP:N,P=1 $Lower BeO Plug
78  4   -2.8000   -18             U=7  IMP:N,P=1 $Upper BeO Plug
79  3   -8.0300    17 -19         U=7  IMP:N,P=1 $Lower SS Plug
80  3   -8.0300    18 -20         U=7  IMP:N,P=1 $Upper SS Plug
81  3   -8.0300    19  20  16 -21  U=7  IMP:N,P=1 $SS304
82  5   -1.0000    21 -22         U=7  IMP:N,P=1 $Water
C
C  Empty Aluminum Rod
C
90  0             -90             U=9  IMP:N,P=1 $Void
91  7   -2.7000    90 -21         U=9  IMP:N,P=1 $Al Rod
92  5   -1.0000    21 -22         U=9  IMP:N,P=1 $Water
C
C  Core  (UNIVERSE = 8)
C
  1  0  -300 311 210 211 213 220  fill=8   IMP:N,P=1
C
  2  5   -1.0000  -320     lat=2   U=8  IMP:N,P=1
             fill -12:12 -12:12 0:0
C
C  This fuel loading reflects the board as of May 2003.
C
                 2 24r
                2 24r
               2 24r
              2 9r 2  6  1      1  1  1  1  1  1  1  1     1  6  2 2   $ interface with frec
             2 8r 6  6  1  1     1  1  1  1  1  1  1     1  1  6  6 2
            2 7r 6  1  1  1  1     1  1  1  1  1  1    1  1  1  1  6 2
           2 6r 6  7  1  1  1  3   1   1  5   1   1  3  1  1  1  7  6 2
          2 5r 6  7  1  1  1  1  1   1  1  1  1   1   1  1  1  1  7  6 2
         2 4r 6  7  1  1  1  1  1   1  1  1  1  1   1  1  1  1  1  7  6 2
        2 3r 9  6  1  1  1  4  1   1   2 2 2 2   1   1  1  1  1  1  6  2 2
       2 2r 2  9  6  1  1  1  1   1   2 2 2 2 2   1   1  1  1  1  6  6  2 2
      2  2 2  6  6  1  1  1  1   1   2 2 2 2 2 2   1   1  1  1  1  6  2  2 2
        2 2  2  6  1  1  3  1   1   2 2 2 2 2 2 2   1   1  3  1  1  6  2  2 2   $ center line
         2 2  6  6  1  1  1  1   1   2 2 2 2 2 2   1   1  1  1  1  9  6  2 2 2
          2 2  6  1  1  1  1  1   1   2 2 2 2 2   1   1  1  1  1  1  9  2 2 2r
           2 6  1  1  1  1  5  1   1   2 2 2 2   1   1  5  1  1  1  1  2 2 3r
            2 6  1  1  1  1  1  1   1  1  1  1  1   1  1  1  1  1  1  2 2 4r
             2 6  1  1  1  1  1  1    1  1  1  1   1  1  1  1  1  1  2 2 5r
              2 6  1  1  1  1  3   1   1  4   1   1  3  1  1  1  1  2 2 6r
               2 6  7  1  1  1     1  1  1  1  1  1    1  1  1  1  2 2 7r
                2 6  6  6  1     1  1  1  1  1  1  1     1  9  9  2 2 8r
                 2 2  9  6      6  6  1  1  1  1  6  6     6  6  2 2 9r
                  2 2  2      9  2  6  7  7  7  6  2  6      2  2 2 10r
                   2 2 2 2        9  6  6  6  6  9         2 2 2 2 11r
                    2 24r
```

```
C
C
C ********  END OF UNIVERSE DEFINITIONS AND CORE FILL  ********
C
C  NEW CENTRAL CAVITY
C
C   To add 32-in pedestal, remove C from line 2.
C   To add 8-in pedestal, remove C from line 2 and 3.
C   You must also remove the C's from the cells in the pedestal
C    descriptions (Cells 110-116).
C
C    Use Line 4 of Cell 100 to exclude surface of buckets and experiments.
C     Exclude surface 706 for Pb-B4C; Exclude surface 711 for Al dosimetry bucket;
C     Exclude surface 725 for LP-1
C     Exclude surfaces 730, 731, and 734 for Boom Box
C
100  702 -1.0245e-3  -100
                      110
                      113 114 116
                      711               IMP:N,P=1 $Void
101  3  -8.0300    100 -101             IMP:N,P=1 $Stainless liner
102  7  -2.7000   -311  101 -102        IMP:N,P=1 $Aluminum
103  5  -1.0000   -311  102             IMP:N,P=1 $Water
C
C
C  Central Cavity Additions (32" and 8" Pedestals)
C
C  32-in pedestal
C
 110  7  -2.7000      -110  111  112        IMP:N,P=1 $32-in pedestal
 111  702 -1.0245e-3  -111                  IMP:N,P=1 $32-in pedestal inset
 112  702 -1.0245e-3  -112                  IMP:N,P=1 $Inset Notch
C
C
C  8-in pedestal
C
 113  7  -2.7000   -113                  IMP:N,P=1 $Bottom plate
 114  7  -2.7000   -114                  IMP:N,P=1 $Top plate
 115  702 -1.0245e-3   -115                  IMP:N,P=1 $Center Void
 116  7  -2.7000   -116  115             IMP:N,P=1 $Support Tube
C
C
C   End of Central Cavity Additions
C
C
C  Top and Bottom Grid Plates
C
200  7  -2.7000   -200  311  201        IMP:N,P=1 $Top plate
201  5  -1.0000   -200  220 -201        IMP:N,P=1 $Water
202  7  -2.7000   -202  311             IMP:N,P=1 $Bottom plate
C
C
C  Nickel Plate and Window to the Radiography Lab
C
210  6  -8.9000   -210                  IMP:N,P=1 $Nickel Plate
211  5  -1.0000   -211  210 -900        IMP:N,P=1 $Water
212  0            -212 -900             IMP:N,P=1 $Void
213  7  -2.7000   -213  212 -900        IMP:N,P=1 $Aluminum
C
C
C  FREC-II Side Ni Plate
C
220  6  -8.9000   -220                  IMP:N,P=1
C
C
C  Surrounding Water
C
230  5  -1.0000   -900  220 213 212 211 202 200
                        300 311         IMP:N,P=1
C
C
C
C
C   EXPERIMENTAL or SPECTRUM MODIFYING BUCKETS  (700's)
C
C  Pb-B4C Bucket  (700-706)
C  Weight of Bucket per L. Martin (8/21/2003) - 446 lbs
C  Weight of Model Bucket                    - 450.81
C  Density of B4C layer changed to 2.12 g/cc to make weight 446.19 lbs
C
C
```

```
C 700  702 -1.0245e-3  -700 -100            IMP:N,P=1 $Inside Bucket
C 701  7   -2.7100  -701  700 -100          IMP:N,P=1 $1/16" Al liner
C 702 700  -11.350  -702 701 7091 7092 -100 IMP:N,P=1 $1" Pb on bottom
C 703 701  -2.5300  -703  7091 7092         IMP:N,P=1 $Boral on bottom
C 707  0            -707  702 -100          IMP:N,P=1 $Slop between Cannister and Pb
C 708  8   -2.1200  -708                    IMP:N,P=1 $B4C layer on the bottom
C
C 704  7   -2.7100  -704  703  707  708
C                        7091 7092 -100    IMP:N,P=1 $Al layer
C 705  8   -2.1200  -705  704      -100    IMP:N,P=1 $B4C layer
C 706  7   -2.7100 -706 705 7091 7092 -100 IMP:N,P=1 $Al exterior
C 7091  3   -8.0300 -7091 -100              IMP:N,P=1 $Dowel 1
C 7092  3   -8.0300 -7092 -100              IMP:N,P=1 $Dowel 2
C
C
C
C  Standard Aluminum Experiment Bucket (710-711)
C   Add -900 to 710 and 711 if using 24" Bucket
C
 710  702 -1.0245e-3  -710                IMP:N,P=1 $Inside Bucket
 711  7   -2.7000     -711  710           IMP:N,P=1 $Aluminum Bucket
C
C
C
C
C  Pb-Poly Bucket (720-725) -- Designated as LP-1
C
C 720  702 -1.0245e-3  -720                IMP:N,P=1 $Bottom of Inside
C 721  7   -2.7000  -721  720  726          IMP:N,P=1 $1/16" Al Liner
C 722  700 -11.350  -722  721  724  726    IMP:N,P=1 $0.4" Pb Layer
C 723  704 -0.9450  -723  722  726          IMP:N,P=1 $0.8" HDPE
C 724  704 -0.9450  -724                    IMP:N,P=1 $HDPE fill-in
C 725  7   -2.7000  -725  721  723  726    IMP:N,P=1 $Al Container
C 726  702 -1.0245e-3  -726                IMP:N,P=1 $Top of Inside
C
C
C
C
C
C  Boombox for NG testing (730-738)
C
C 730  765 -7.28    -730  736  737  738    IMP:N,P=1 $Lower Boom Box
C 731  765 -7.28    -731  733              IMP:N,P=1 $Upper part of clamping ring
C 732  765 -7.28    -732  733              IMP:N,P=1 $Lower part of clamping ring
C 733  702 -1.0245e-3  -733                IMP:N,P=1 $"Void" in clamping ring
C 734  702 -1.0245e-3  -734 732            IMP:N,P=1 $"Void" at ring lip
C 735  765 -7.28    -735                    IMP:N,P=1 $Plug
C 736  702 -1.0245e-3  -736 735            IMP:N,P=1 $"Void" around the plug
C 737  702 -1.0245e-3  -737                IMP:N,P=1 $Lower "void"
C 738  702 -1.0245e-3  -738                IMP:N,P=1 $Lip "void"
C
C
C     EXPERIMENT PACKAGES (1000's)
C
C
C
C
C     EXTERNAL WORLD
C
C
C
900 0             900                     IMP:N,P=0 $Outside world

C ******************************************************************
C *                         SURFACE CARDS                          *
C ******************************************************************
C
C    Fuel Elements
C
10  RCC  0.000  0.000  23.32  0.000  0.000  52.25  0.2413  $Void
11  RCC  0.000  0.000  23.32  0.000  0.000  52.25  1.6840  $Fuel
14  RCC  0.000  0.000  23.32  0.000  0.000  52.25 1.72025  $Void
15  RCC  0.000  0.000  23.32  0.000  0.000  52.25 1.77125  $Niobium
16  RCC  0.000  0.000  23.32  0.000  0.000  52.25 1.82225  $Void gap
17  RCC  0.000  0.000 21.415  0.000  0.000  1.905 1.48700  $Lower plug
18  RCC  0.000  0.000  75.57  0.000  0.000  1.905 1.48700  $Upper plug
19  RCC  0.000  0.000  16.32  0.000  0.000  7.000 1.82225  $Lower plug
20  RCC  0.000  0.000  75.57  0.000  0.000  5.000 1.82225  $Upper plug
21  RCC  0.000  0.000  16.32  0.000  0.000  98.89 1.87325  $
22  RCC  0.000  0.000  16.32  0.000  0.000  98.89 5.00000  $Water
C
```

```
C   Control Rods
C
25 3 RCC 0.000  0.000  78.11  0.000  0.000  52.25 1.46050  $B4C poison
26 3 RCC 0.000  0.000  78.11  0.000  0.000  98.89 1.50495  $Void cap
27 3 RCC 0.000  0.000  78.11  0.000  0.000  98.89 1.74625  $poison sleeve
28 3 RCC 0.000  0.000  75.57  0.000  0.000   2.54 1.74625  $Magnaform plug
29 3 RCC 0.000  0.000  75.57  0.000  0.000 101.43 5.00000  $Water
30 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 0.24130  $Void
31 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.68400  $Fuel
32 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.72025  $Void
33 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.77125  $Niobium
34 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.82225  $Void gap
35 3 RCC 0.000  0.000  20.78  0.000  0.000   2.54 1.82225  $BeO plug
36 3 RCC 0.000  0.000 -79.22  0.000  0.000 100.00 1.82225  $Void
37 3 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 1.87325  $SS304
38 3 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 5.00000  $Water
C
C    Safety Rods
C
39 4 RCC 0.000  0.000  78.11  0.000  0.000  52.25 0.57150  $B4C poison
40 4 RCC 0.000  0.000  78.11  0.000  0.000  98.89 0.83185  $Void cap
41 4 RCC 0.000  0.000  78.11  0.000  0.000  98.89 1.74625  $Poison sleeve
42 4 RCC 0.000  0.000  75.57  0.000  0.000   2.54 1.74625  $Magnaform plug
43 4 RCC 0.000  0.000  75.57  0.000  0.000 101.43 5.00000  $Water
44 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 0.24130  $Void
45 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.68400  $Fuel
46 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.72025  $Void
47 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.77125  $Niobium
48 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.82225  $Void gap
49 4 RCC 0.000  0.000  20.78  0.000  0.000   2.54 1.82225  $BeO plug
50 4 RCC 0.000  0.000 -79.22  0.000  0.000 100.00 1.82225  $Void
51 4 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 1.87325  $SS304
52 4 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 5.00000  $Water
C
C    Transient Rods
C
53 5 RCC 0.000  0.0 -76.2762  0.000  0.0  73.1012 1.20000  $Void
54   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 1.27000  $Al tubing
55   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 1.49860  $Water
56   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 2.02438  $Al guidex
57   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 5.00000  $Water
58 5 RCC 0.000  0.000 -3.175  0.000  0.000   3.174 1.20000
59 5 RCC 0.000  0.000 -0.001  0.000  0.000 76.201 0.88000  $Poison
60 5 RCC 0.000  0.000 -0.001  0.000  0.000 76.201 1.20000  $Inner sleeve
61 5 RCC 0.000  0.000  76.20  0.000  0.000 123.80 1.20000  $Void
62 5 RCC 0.000  0.000 -100.0  0.000  0.00 23.7238 1.20000  $End plug
C
C    Aluminum Rods
C
90  RCC  0.000  0.000  15.41  0.000  0.000  66.14 1.77125  $Void in Al rod
C
C    Central Cavity Surfaces
C
100 RCC  0.000  0.000  0.000  0.000  0.000  95.00 11.6450  $Void
101 RCC  0.000  0.000  0.000  0.000  0.000  95.00 12.2800
102 RCC  0.000  0.000  0.000  0.000  0.000  95.00 13.9700
C
C   Cavity Additions
C
110 RCC  0.000  0.000  0.000  0.000  0.000 13.885 11.4300  $32-in pedestal
111 RCC  0.000  0.000 8.4748  0.000  0.000 2.8702  8.2550  $32-in inset
112 RPP -0.9525 0.9525  -8.255  8.255  11.345  13.885      $Inset Notch
113 RCC  0.000  0.000 13.885  0.000  0.000   1.270 10.3188  $Bottom plate (8-in)
114 RCC  0.000  0.000 32.935  0.000  0.000   1.270 10.3188  $Top plate (8-in)
115 RCC  0.000  0.000 15.155  0.000  0.000   17.78  5.7150  $Center void (8-in)
116 RCC  0.000  0.000 15.155  0.000  0.000   17.78  6.3500  $Support tube (8-in)
C
C    Top and Bottom Grid Plates
C
200 RCC  0.000  0.000  80.55  0.000  0.000   2.54 53.3500  $Top plate
201 PY  -34.925                                          $Cutoff of top plate
202 RCC  0.000  0.000  11.33  0.000  0.000   5.08 47.0000  $Bottom plate
C
C
C    Window to Radiography Lab
C
210  1 RPP  38.100 39.370  -26.670 26.670  16.41 80.55     $Ni plate
211  1 RPP  38.100 39.370  -38.100 38.100  16.41 80.55     $Water
212  1 RPP  48.895 100.00  -26.670 26.670  16.41 80.55     $Void
213  1 RPP  39.370 100.00  -38.100 38.100  16.41 80.55     $Aluminum
C
```

```
C   Nickel Plate near FREC-II
C
220  RPP  -36.830 36.830  -36.195 -34.925  16.41 83.09     $Nickel Plate
C
C    Hexes for the lattice, inner and outer core, and core boundary
C
320  RHP  0.0 0.0 -132.0  0.0 0.0 400.0 2.0855 0.0 0.0    $Lattice element
300  1 RHP  0.0 0.0 16.41 0.0 0.0 64.14 42.7 0.0 0.0      $outer core bound
310  1 RHP  0.0 0.0 0.0   0.0 0.0 95.00 11.65 0. 0.0      $Inner liner of cavity
311  1 RHP  0.0 0.0 0.0   0.0 0.0 95.00 12.285 0. 0.      $Outer liner of cavity
C
C
C   Buckets  (700's)
C
C  Pb-B4C Bucket
C
 700 7 RCC  0.0 0.0 6.35     0.0 0.0 85.09    6.27380 $Void
 701 7 RCC  0.0 0.0 6.26872  0.0 0.0 85.17128 6.35508 $0.032" Al liner
 702 7 RCC  0.0 0.0 3.65125  0.0 0.0 87.78875 9.76630 $Pb layers
 703 7 RCC  0.0 0.0 3.01625  0.0 0.0  0.63500 9.17575 $Boral
 704 7 RCC  0.0 0.0 1.90500  0.0 0.0 89.53500 10.1600 $Al layer
 705 7 RCC  0.0 0.0 1.90500  0.0 0.0 89.53500 11.1125 $B4C
 706 7 RCC  0.0 0.0 0.00000  0.0 0.0 91.44000 11.4300 $Al layer
 707 7 RCC  0.0 0.0 3.65125  0.0 0.0 87.78875 9.84250
 708 7 RCC  0.0 0.0 1.90500  0.0 0.0  0.63500 7.62000 $B4C bottom
7091 7 RCC  0.0 -8.890 0.00  0.0 0.0 91.44000 0.31750 $Dowel 1
7092 7 RCC  0.0  8.890 0.00  0.0 0.0 91.44000 0.31750 $Dowel 2
C
C  14" Aluminum Bucket
C
 710 7 RCC  0.0 0.0 0.15875  0.0 0.0 35.40125 11.27125   $Void
 711 7 RCC  0.0 0.0 0.00000  0.0 0.0 35.56000 11.43000   $Al bucket
C
C USE these for a 24" Aluminum Bucket
C
C 710 7 RCC  0.0 0.0 0.15875  0.0 0.0 60.80125 11.27125   $Void
C 711 7 RCC  0.0 0.0 0.00000  0.0 0.0 60.96000 11.43000   $Al bucket
C
C  LP-1 Surfaces
C
 720 7 RCC  0.0 0.0 5.74675  0.0 0.0 62.18825  7.46125   $Inside
 721 7 RCC  0.0 0.0 5.58800  0.0 0.0 73.15200  7.62000   $Al liner
 722 7 RCC  0.0 0.0 3.55600  0.0 0.0 64.37900  8.63600   $Pb
 723 7 RCC  0.0 0.0 2.54000  0.0 0.0 65.39500 10.66800   $HDPE
 724 7 RCC  0.0 0.0 3.55600  0.0 0.0  1.01600  7.62000   $HDPE fill-in
 725 7 RCC  0.0 0.0 0.00000  0.0 0.0 78.74000 11.43000   $Al Container
 726 7 RCC  0.0 0.0 67.9350  0.0 0.0 10.80500  7.46125
C
C  Boom Box Surfaces
C
 730  7 RCC  0.0 0.0 0.0      0.0 0.0 65.786   9.8425
 731  7 RCC  0.0 0.0 65.913   0.0 0.0  3.048   9.8425
 732  7 RCC  0.0 0.0 65.786   0.0 0.0  0.127   8.1280
 733  7 RCC  0.0 0.0 65.786   0.0 0.0  3.175   5.0800
 734  7 RCC  0.0 0.0 65.786   0.0 0.0  0.127   9.8425
 735  7 RCC  0.0 0.0 59.436   0.0 0.0  6.350   6.6675
 736  7 RCC  0.0 0.0 59.436   0.0 0.0  6.350   6.7945
 737  7 RCC  0.0 0.0  2.540   0.0 0.0 54.864   7.9375
 738  7 RCC  0.0 0.0 57.404   0.0 0.0  2.032   5.0800
C
C
C  EXPERIMENT SURFACES
C
C
C    External Cutoff
C
900 RCC  0.000  0.000  0.000  0.000  0.000  95.00 72.0000

C ******************************************************************
C *                          DATA CARDS                            *
C ******************************************************************
MODE N
KCODE   10000 1 15 315 11000
KSRC   20 0 50  0 20 60  30 0 40  0 30 60
C *************************
C *     TRANSFORMATIONS    *
C *************************
C
C  TR1 rotates the hexes for the outer core bound and the cavity liner
C
*TR1   0 0 0 30 60 90 120 30 90
```

```
C
C  TR3-->Movement of control rods -0.001 (full up) to -55.001 (full down)
C
C
C   Measured Up DC with 32-in pedestal is -39.731               (03/03/2004)
C   Measured Down DC is -30.851                                 (03/03/2004)
C    -->Up DC position of 1527 Rod Units
C    -->Down DC position of 2415 Rod Units
C   Measured Up DC with 8-in + 32-in pedestal is -40.421        (03/01/2004)
C   Measured Down DC with 8-in + 32-in pedestal is -31.291      (03/01/2004)
C    -->Up DC position of 1428 Rod Units
C    -->Down DC position of 2371 Rod Units
C   Measured Up DC with Pb-B4C on 32-in pedestal is -22.951     (03/09/2004)
C   Measured Down DC with Pb-B4C on 32-in pedestal is -10.741   (03/09/2004)
C    -->Up DC position of 3205 Rod Units
C    -->Down DC position of 4426 Rod Units
C   Measured DC with LP-1 on 32-in pedestal is -31.941          (03/11/2004)
C   Measured Down DC with LP-1 on 32-in pedestal is -23.721     (03/11/2004)
C    -->Up DC position of 2306 Rod Units
C    -->Down DC position of 3128 Rod Units
C
*TR3   0 0 -41.6
C
C  TR4-->Movement of safety rods 0.001 (full up) to -54.999 (full down)
C
C    Measured worth of safety rods:  -$2.12                     (03/30/2004)
C
*TR4   0 0  0.001
C
C  TR5-->Movement of transient rods 0 (full down) to 90 (full up)
C
C    Measured worth of transient rods:  -$4.14                  (03/30/2004)
C
*TR5   0 0  90
C
C  TR6-->Moves experiment package from origin (0 0 0) to fuel centerline
C
*TR6   0  0  49.445
C
C  TR7-->Puts buckets on 8" (34.205) or 32" (13.885) pedestals
C   Use 32" pedestal for LP-1
C   Use 8" for Standard Al buckets
C
*TR7   0  0  34.205
C
C *******************
C *  MATERIAL CARDS  *
C *******************
C  Materials cards use the latest available cross sections
C
C  UO2-BeO fuel (3.3447 g/cc)  (XSEC Temp - 293.6 K)
C
M1      4009.62c -0.2827602   8016.62c -0.5277690  92235.66c -0.0662957
       92238.66c -0.1222844  92234.66c -0.0004547  92236.66c -0.0004358
MT1     beo.60t      $ S(alpha, beta) for BeO (Temp - 294 K)
C
C  UO2-BeO fuel (3.0102 g/cc)  -- This is the 90% fuel
C                                 (XSEC Temp - 293.6 K)
C   Included as a separate material to avoid warning message
C
M11     4009.62c -0.2827602   8016.62c -0.5277690  92235.66c -0.0662957
       92238.66c -0.1222844  92234.66c -0.0004547  92236.66c -0.0004358
MT11    beo.60t      $ S(alpha, beta) for BeO (Temp - 294 K)
C
C     NIOBIUM (8.4 g/cc)
C
M2     41093.66c  1.0000
C
C
C  SS-304L from Ktech Materials Database Rev. 118
C   Material Number:  3410
C     Values are weight %
C      Si: 0.0100  Cr: 0.1900  Mn: 0.0200  Fe: 0.6800  Ni: 0.1000
C
C FM multiplier (neutrons):  1.76109641E-10  3410  -4   1
C FM multiplier (photons):   1.76109641E-10  3410  -5  -6
C
C  Density:  7.896 g/cc
C
M3     14028.62c -0.009187  14029.62c -0.000483  14030.62c -0.000329
       24050.62c -0.007930  24052.62c -0.159029  24053.62c -0.018380
```

```
       24054.62c -0.004661  25055.62c -0.020000  26054.62c -0.038390
       26056.62c -0.624930  26057.62c -0.014691  26058.62c -0.001989
       28058.62c -0.067198  28060.62c -0.026776  28061.62c -0.001183
       28062.62c -0.003834  28064.62c -0.001009
C
C     BeO (2.8 g/cc)
C
M4      4009.62c  0.5000     8016.62c  0.4998096    8017.66c  0.0001904
MT4     beo.60t      $ S(alpha, beta) for BeO (Temp - 294 K)
C
C     Water (1 g/cc)
C
M5    1001.62c  0.6665667    1002.66c  0.000100
      8016.62c  0.3332063    8017.66c  0.000127
MT5     lwtr.60t     $ S(alpha, beta) for water (Temp - 294 K)
C
C  Ni reflector
C           Values are weight %
C           Ni-58: 67.19780  Ni-60: 26.77586  Ni-61:  1.18346
C           Ni-62:  3.83429  Ni-64:  1.00859
C    Converted Data from Nuclear Wallet Card to w/o with "Weight_Frac" program
C  Density:  8.9020 g/cc
C
C
M6    28058.62c -0.6719780 28060.62c -0.2677586 28061.62c -0.0118346
      28062.62c -0.0383429 28064.62c -0.0100859
C
C
C  Al-6061 from Ktech Materials Database Rev. 118
C    Material Number:  3110
C     Values are weight %
C      Mg: 0.0110  Al: 0.9670  Si: 0.0080  Ti: 0.0007
C      Cr: 0.0020  Mn: 0.0013  Fe: 0.0056  Ni: 0.0004
C      Cu: 0.0030  Zn: 0.0010
C
C FM multiplier (neutrons):  3.55249469E-10  3110  -4   1
C FM multiplier (photons):   3.55249469E-10  3110  -5  -6
C
C  Density:  2.704 g/cc
C
M7     12000.62c -0.011000  13027.62c -0.967000  14028.62c -0.007350
       14029.62c -0.000387  14030.62c -0.000263  22000.62c -0.000700
       24050.62c -0.000084  24052.62c -0.001674  24053.62c -0.000193
       24054.62c -0.000049  25055.62c -0.001300  26054.62c -0.000316
       26056.62c -0.005147  26057.62c -0.000121  26058.62c -0.000016
       28058.62c -0.000269  28060.62c -0.000107  28061.62c -0.000005
       28062.62c -0.000015  28064.62c -0.000004  29063.62c -0.002055
       29065.62c -0.000945  30000.42c -0.001000
C
C    B4C poison (2.48 g/cc)
C
M8      6000.66c  0.20000   5010.66c  0.159200   5011.66c  0.640800
C
C
C  Natural Lead
C  True Weight %:  Pb-204:  1.37808  Pb-206: 23.95550
C                  Pb-207: 22.07430  Pb-208: 52.59212
C  Weight % based on Available MCNP XSEC:
C                  Pb-206: 24.29024  Pb-207: 22.38275
C                  Pb-208: 53.32701
C
C    Converted Data from Nuclear Wallet Card to w/o with "Weight_Frac" program
C  Density is 11.35 g/cc from Nuclear Wallet Cards.
C
C
M700  82206.66c -0.2429024  82207.66c -0.2238275
      82208.66c -0.5332701
C
C Boral Plate Composition
C
C  Composition found in Nuclear Science and Engineering
C   Vol. 65, No. 1, pgs. 41-48, January 1978.
C   Values are weight %
C        B: 27.40   C:  7.61  Al: 63.68
C       Cu:  0.09  Zn:  0.16  Fe:  0.45
C       Cr:  0.10  Mn:  0.10  Mg:  0.05
C       Ti:  0.10  Li:  0.26
C
C   Density:  2.53 g/cc
C
M701   5010.66c -0.050242   5011.66c -0.223758    6000.66c -0.076100
```

```
      13027.62c -0.636800  29063.62c -0.000616   29065.62c -0.000284
      30000.42c -0.001600  26056.62c -0.004500   24050.62c -0.000042
      24052.62c -0.000837  24053.62c -0.000097   24054.62c -0.000024
      25055.62c -0.001000  12000.62c -0.000500   22000.62c -0.001000
       3006.66c -0.000171   3007.66c -0.002429
C
C  Air
C   Standard Density:  1.205e-3 g/cc @ 20 deg C, 1 atm
C   Albuquerque:       1.0245e-3 g/cc in ABQ
C  See Attix p.531-532
C
M702   7014.62c -0.752308   7015.66c -0.002960   8016.62c -0.231687
       8017.66c -0.000094   6000.66c -0.000124  18000.42c -0.012827
C
C
C   HELIUM  For Leak Test
C    @ 2 atm density = 3.57e-4 g/cc
C
M703   2003.66c 0.00000137  2004.62c  0.99999863
C
C
C HDPE-> (C2H4)n    --          --
C                  |   H    H   |
C                  |   |    |   |
C                 -|-  C -- C  -|-
C                  |   |    |   |
C                  |   H    H   |
C                  --          --
C
M704   1001.60c  0.666667   6000.60c  0.333333
MT704  poly.01t
C
C   A517 Carbon Steel  (den = 7.28 g/cc)
C     Modified to match the mill test cert.
C     from Tubos de Acero de Mexico, S.A.
C
C   Summary of MatMCNP Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C   C-12       0.0118115          0.0025688          0.0009385
C   C-13       0.0001326          0.0000312          0.0000105
C  Si-28       0.0048924          0.0024807          0.0003887
C  Si-29       0.0002484          0.0001305          0.0000197
C  Si-30       0.0001638          0.0000890          0.0000130
C  Cr-50       0.0000184          0.0000167          0.0000015
C  Cr-52       0.0003557          0.0003348          0.0000283
C  Cr-53       0.0000403          0.0000387          0.0000032
C  Cr-54       0.0000100          0.0000098          0.0000008
C  Mn-55       0.0078340          0.0078003          0.0006225
C  Fe-54       0.0568920          0.0556172          0.0045205
C  Fe-56       0.8930822          0.9053674          0.0709617
C  Fe-57       0.0206252          0.0212829          0.0016388
C  Fe-58       0.0027448          0.0028820          0.0002181
C  Cu-63       0.0007628          0.0008700          0.0000606
C  Cu-65       0.0003400          0.0004001          0.0000270
C  Mo-92       0.0000068          0.0000114          0.0000005
C  Mo-94       0.0000043          0.0000072          0.0000003
C  Mo-95       0.0000073          0.0000126          0.0000006
C  Mo-96       0.0000077          0.0000133          0.0000006
C  Mo-97       0.0000044          0.0000077          0.0000003
C  Mo-98       0.0000111          0.0000197          0.0000009
C  Mo-100      0.0000044          0.0000080          0.0000004
C
C  The total compound atom density (atom/b-cm):  0.07945702
C
M765    06000.66c  0.0119440  14028.62c  0.0048924  14029.62c  0.0002484
        14030.62c  0.0001638  24050.62c  0.0000184  24052.62c  0.0003557
        24053.62c  0.0000403  24054.62c  0.0000100  25055.62c  0.0078340
        26054.62c  0.0568920  26056.62c  0.8930822  26057.62c  0.0206252
        26058.62c  0.0027448  29063.62c  0.0007628  29065.62c  0.0003400
        42000.66c  0.0000460
C
C ********************
C *     TALLIES      *
C ********************
C
PRINT  10 60 100
```

LEFT BLANK INTENTIONALLY

APPENDIX B – MCNP MODEL OF ACRR (FREC-II COUPLED)

```
Standard ACRR Model with FREC-II
C
C  Model Developed by R. DePriest (845-8141)
C
C  This model was created using the macrobody feature of MCNP.  There are
C    spectrum modifying buckets included in the model.
C
C  FREC elements are defined using macrobodies.  The other cells were
C    created using surfaces.  FREC-II model is based on work by E. Parma
C    and P. Cooper.
C
C  There will be warnings about surfaces being the same and unused
C   surfaces.  This is a by-product of the macrobodies and the flexibility
C   of using various experiment buckets.
C
C ********************************************************************
C *                          CELL CARDS                              *
C ********************************************************************
C
C *  Universe definitions for standard 236-element core. *
C
C     U=1:fuel rods              U=2:water rods
C     U=3:control rods           U=4:safety rods
C     U=5:transient rods         U=6:nickel rods
C     U=7:90% fuel rods          U=9:al rods (empty)
C
C   ********  U=8 is the reactor core fill.  *******
C
C  Regular Fuel Element
C
10  0             -10              U=1  IMP:N,P=1 $He-Void
11  1   -3.3447    10 -11          U=1  IMP:N,P=1 $UO2-BeO fuel
14  0              11 -14          U=1  IMP:N,P=1 $He-Void
15  2   -8.5700    14 -15          U=1  IMP:N,P=1 $Niobium
16  0              15 -16          U=1  IMP:N,P=1 $He-Void Gap
17  4   -2.8000   -17              U=1  IMP:N,P=1 $Lower BeO Plug
18  4   -2.8000   -18              U=1  IMP:N,P=1 $Upper BeO Plug
19  3   -7.8960    17 -19          U=1  IMP:N,P=1 $Lower SS Plug
20  3   -7.8960    18 -20          U=1  IMP:N,P=1 $Upper SS Plug
21  3   -7.8960    19  20  16 -21  U=1  IMP:N,P=1 $SS304
22  5   -1.0000    21 -22          U=1  IMP:N,P=1 $Water
C
C  Water Rods
C
23  5   -1.0000   -22              U=2  IMP:N,P=1 $Water
C
C  Control Rods:  Poison section
C
25  8   -2.4800   -25              U=3  IMP:N,P=1 $B4C poison
26  0              25 -26          U=3  IMP:N,P=1 $He-Void Cap
27  3   -7.8960    26 -27          U=3  IMP:N,P=1 $Poison sleeve
28  3   -7.8960   -28              U=3  IMP:N,P=1 $Magnaform plug
29  5   -1.0000    27  28 -29      U=3  IMP:N,P=1 $Water
C
C  Control Rods:  Fuel follower
C
30  0             -30              U=3  IMP:N,P=1 $He-Void
31  1   -3.3447    30 -31          U=3  IMP:N,P=1 $UO2-BeO fuel
32  0              31 -32          U=3  IMP:N,P=1 $He-Void
33  2   -8.5700    32 -33          U=3  IMP:N,P=1 $Niobium
34  0              33 -34          U=3  IMP:N,P=1 $He-Void gap
35  4   -2.8000   -35              U=3  IMP:N,P=1 $BeO plug
36  0             -36              U=3  IMP:N,P=1 $Void
37  3   -7.8960    34  35 36 -37   U=3  IMP:N,P=1 $SS304
38  5   -1.0000    37 -38          U=3  IMP:N,P=1 $Water
C
C  Safety Rods:  Poison section
C
39  8   -2.4800   -39              U=4  IMP:N,P=1 $B4C poison
40  0              39 -40          U=4  IMP:N,P=1 $He-Void cap
41  3   -7.8960    40 -41          U=4  IMP:N,P=1 $Poison sleeve
42  3   -7.8960   -42              U=4  IMP:N,P=1 $Magnaform plug
43  5   -1.0000    41  42 -43      U=4  IMP:N,P=1 $Water
C
C  Safety Rods:  Fuel follower
C
44  0             -44              U=4  IMP:N,P=1 $He-Void
```

```
45  1   -3.3447    44 -45          U=4  IMP:N,P=1 $UO2-BeO fuel
46  0              45 -46          U=4  IMP:N,P=1 $He-Void
47  2   -8.5700    46 -47          U=4  IMP:N,P=1 $Niobium
48  0              47 -48          U=4  IMP:N,P=1 $He-Void gap
49  4   -2.8000   -49              U=4  IMP:N,P=1 $BeO plug
50  0             -50              U=4  IMP:N,P=1 $He-Void
51  3   -7.8960    48 49  50 -51   U=4  IMP:N,P=1 $SS304
52  5   -1.0000    51 -52          U=4  IMP:N,P=1 $Water
C
C  Transient Rods:  Void section
C
53  0             -53              U=5  IMP:N,P=1 $He-Void
54  7   -2.7040    53 -54 58 60 61 U=5  IMP:N,P=1 $Al tubing
55  5   -1.0000    54 -55          U=5  IMP:N,P=1 $Water
56  7   -2.7040    55 -56          U=5  IMP:N,P=1 $Al guidex
57  5   -1.0000    56 -57          U=5  IMP:N,P=1 $Water
58  7   -2.7040   -58              U=5  IMP:N,P=1
C
C  Transient Rods:  Poison section
C
59  8   -2.4800   -59              U=5  IMP:N,P=1 $Poison
60  7   -2.7000    59 -60          U=5  IMP:N,P=1 $Inner sleeve
61  0             -61              U=5  IMP:N,P=1 $He-Void
62  7   -2.7040   -62  54          U=5  IMP:N,P=1 $End plug
C
C  Nickel Rods
C
65  6   -8.9020   -21              U=6  IMP:N,P=1 $Nickel
66  5   -1.0000    21 -22          U=6  IMP:N,P=1 $Water
C
C  90% Fuel Element
C
70  0             -10              U=7  IMP:N,P=1 $He-Void
71  11  -3.0102    10 -11          U=7  IMP:N,P=1 $UO2-BeO fuel
74  0              11 -14          U=7  IMP:N,P=1 $He-Void
75  2   -8.5700    14 -15          U=7  IMP:N,P=1 $Niobium
76  0              15 -16          U=7  IMP:N,P=1 $He-Void Gap
77  4   -2.8000   -17              U=7  IMP:N,P=1 $Lower BeO Plug
78  4   -2.8000   -18              U=7  IMP:N,P=1 $Upper BeO Plug
79  3   -7.8960    17 -19          U=7  IMP:N,P=1 $Lower SS Plug
80  3   -7.8960    18 -20          U=7  IMP:N,P=1 $Upper SS Plug
81  3   -7.8960    19  20  16 -21  U=7  IMP:N,P=1 $SS304
82  5   -1.0000    21 -22          U=7  IMP:N,P=1 $Water
C
C  Empty Aluminum Rod
C
90  0             -90              U=9  IMP:N,P=1 $Void
91  7   -2.7040    90 -21          U=9  IMP:N,P=1 $Al Rod
92  5   -1.0000    21 -22          U=9  IMP:N,P=1 $Water
C
C   Solid Aluminum Rod
C
93  7   -2.7040   -21              U=10  IMP:N,P=1 $Aluminum
94  5   -1.0000    21 -22          U=10  IMP:N,P=1 $Water
C
C  Core  (FILL = 8)
C
  1  0  -300 3101 311 210 211 213 220  fill=8   IMP:N,P=1
C
C   LATTICE Definition for ACRR Core (UNIVERSE = 8)
C
  2  5   -1.0000  -320     lat=2   U=8  IMP:N,P=1
             fill -12:12 -12:12 0:0
C
C  This fuel loading reflects the board as of May 2003.
C
C  Al rods added to core so that FREC-II could be mated with ACRR
C
                2 24r
               2 24r
              2 10r 2 2 10   10 10 10   10  10 10 10    10  2  2 2
             2 9r 2  6  1      1  1  1  1  1  1  1  1     1  6  2 2   $ interface with frec
            2 8r 6  6  1  1     1  1  1  1  1  1  1     1  1  6  6 2
           2 7r 6  1  1  1  1     1  1  1  1  1  1    1  1  1  1  6 2
          2 6r 6  7  1  1  1  3   1   1  5   1   1  3  1  1  1  7  6 2
         2 5r 6  7  1  1  1  1  1   1  1  1  1   1   1  1  1  1  7  6 2
        2 4r 6  7  1  1  1  1  1   1  1  1  1  1   1  1  1  1  1  7  6 2
       2 3r 9  6  1  1  1  4  1   1   2 2 2 2   1   1  1  1  1  1  6  2 2
      2 2r 2  9  6  1  1  1  1   1   2 2 2 2 2   1   1  1  1  1  6  6  2 2
     2  2 2  6  6  1  1  1  1   1   2 2 2 2 2 2   1   1  1  1  1  6  2  2 2
       2 2  2  6  1  1  3  1   1   2 2 2 2 2 2 2   1   1  3  1  1  6  2  2 2   $ center line
```

```
        2 2  6  6  1  1  1  1   1   2 2 2 2 2 2   1   1  1  1  1  9  6  2 2 2
         2 2  6  1  1  1  1  1   1   2 2 2 2 2   1   1  1  1  1  1  9  2 2 2r
          2 6  1  1  1  1  5  1   1   2 2 2 2   1   1  5  1  1  1  1  2 2 3r
           2 6  1  1  1  1  1  1   1  1  1  1  1   1  1  1  1  1  1  2 2 4r
            2 6  1  1  1  1  1  1   1  1  1  1   1  1  1  1  1  1  2 2 5r
             2 6  1  1  1  1  3   1   1  4   1   1  3  1  1  1  1  2 2 6r
              2 6  7  1  1  1    1  1  1  1  1  1    1  1  1  1  2 2 7r
               2 6  6  6  1    1  1  1  1  1  1  1    1  9  9  2 2 8r
                2 2  9  6     6  6  1  1  1  1  6  6    6  6  2 2 9r
                 2 2  2     9  2  6  7  7  7  6  2  6     2  2 2 10r
                  2 2 2 2       9  6  6  6  6  9        2 2 2 2 11r
                   2 24r
C
C
C *       END OF UNIVERSE DEFINITIONS AND CORE FILL      *
C
C
C  NEW CENTRAL CAVITY
C
C   To add 32-in pedestal, remove C from line 2.
C   To add 8-in pedestal, remove C from line 2 and 3.
C   You must also remove the C's from the cells in the pedestal
C    descriptions (Cells 110-116).
C
C    Use Line 4 of Cell 100 to exclude surface of buckets and experiments.
C     Exclude surface 706 for Pb-B4C; Exclude surface 711 for Al dosimetry bucket;
C     Exclude surface 725 for LP-1
C     Exclude surfaces 730, 731, and 734 for Boom Box
C
100  702 -1.0245e-3  -100
                      110
C                   113 114 116
                                    IMP:N,P=1 $Air
101  3  -7.8960    100 -101         IMP:N,P=1 $Stainless liner
102  7  -2.7040   -311  101 -102    IMP:N,P=1 $Aluminum
103  5  -1.0000   -311  102         IMP:N,P=1 $Water
C
C
C  Central Cavity Additions (32" and 8" Pedestals)
C
C  32-in pedestal
C
 110  7  -2.7040      -110  111  112        IMP:N,P=1 $32-in pedestal
 111  702 -1.0245e-3  -111                  IMP:N,P=1 $32-in pedestal inset
 112  702 -1.0245e-3  -112                  IMP:N,P=1 $Inset Notch
C
C
C  8-in pedestal
C
C 113  7  -2.7040   -113                 IMP:N,P=1 $Bottom plate
C 114  7  -2.7040   -114                 IMP:N,P=1 $Top plate
C 115 702 -1.0245e-3  -115               IMP:N,P=1 $Center Void
C 116  7  -2.7040   -116  115            IMP:N,P=1 $Support Tube
C
C
C   End of Central Cavity Additions
C
C
C
C  Top and Bottom Grid Plates
C
200  7  -2.7040   -200  311  201        IMP:N,P=1 $Top plate
201  5  -1.0000   -200  220 -201 3101 #204   IMP:N,P=1 $Water
202  7  -2.7040   -202  311 3101        IMP:N,P=1 $Bottom plate
203  7  -2.7040   -202 2821 -3101 311   IMP:N,P=1 $Bottom plate
204  7  -2.7040   -200 2821 -201 311    IMP:N,P=1 $Top plate
C
C
C  Nickel Plate and Window to the Radiography Lab
C
210  6  -8.9020   -210                  IMP:N,P=1 $Nickel Plate
211  5  -1.0000   -211  210 -900        IMP:N,P=1 $Water
212 702 -1.0245e-3  -212 -900           IMP:N,P=1 $Void
213  7  -2.7020   -213  212 -900        IMP:N,P=1 $Aluminum
C
C
C  FREC-II Side Ni Plate -- This is when frec is not in place
C
C 220  6  -8.9020   -220                 IMP:N,P=1
C
C
```

```
C  FREC Side Interface Plate
C
 220  7 -2.7040  -220                     IMP:N,P=1
 221  5 -1.0000  -221 220 -900            IMP:N,P=1
C
C  ACRR Surrounding Water
C
C
230  5  -1.0000   -900   213 212 211 202 200
                        300 311 3101 #204   IMP:N,P=1
231  5  -1.0000   -900  2821 -3101 220 221
                        #203 #204           IMP:N,P=1
C
C
C ****************************************************
C *                                                  *
C *               FREC-II CELL DEFINITIONS           *
C *                                                  *
C ****************************************************
C
C  Universe definitions for the FREC-II core.
C
C     U=20:nominal fuel rods     U=21:raised fuel rods
C     U=22:safety rods           U=23:water rods
C
C
C   ********  U=50 is the FREC-II core fill.  *******
C
C  Nominal FREC-II Fuel Element
C
 400  22 -6.500   -400            U=20  IMP:N,P=1 $Zr rod
 401  21 -6.315   -401  400       U=20  IMP:N,P=1 $U-ZrH fuel
 402  23 -1.600   -402            U=20  IMP:N,P=1 $Lower graphite
 403  23 -1.600   -403            U=20  IMP:N,P=1 $Upper graphite
 404   0          -404            U=20  IMP:N,P=1 $Upper gap
 405   0          -405  404  403
                        402  401  U=20  IMP:N,P=1 $Gap
 406  25 -7.896  -406             U=20  IMP:N,P=1 $Lower SS plug
 407  25 -7.896  -407             U=20  IMP:N,P=1 $Upper SS plug
 408  25 -7.896  -408  407  406
                        405       U=20  IMP:N,P=1 $SS clad
 409  24 -1.00    -409  408       U=20  IMP:N,P=1 $Water-FREC
C
C  Raised FREC-II Fuel Element
C
 410  22 -6.500   -410            U=21  IMP:N,P=1 $Zr rod
 411  21 -6.315   -411  410       U=21  IMP:N,P=1 $U-ZrH fuel
 412  23 -1.600   -412            U=21  IMP:N,P=1 $Lower graphite
 413  23 -1.600   -413            U=21  IMP:N,P=1 $Upper graphite
 414   0          -414            U=21  IMP:N,P=1 $Upper gap
 415   0          -415  414  413
                        412  411  U=21  IMP:N,P=1 $Gap
 416  25 -7.896   -416            U=21  IMP:N,P=1 $Lower SS plug
 417  25 -7.896   -417            U=21  IMP:N,P=1 $Upper SS plug
 418  25 -7.896   -418  417  416
                        415       U=21  IMP:N,P=1 $SS clad
 419  24 -1.00    -409  418       U=21  IMP:N,P=1 $Water-FREC
C
C  FREC-II Fuel Follower and Safety Rod
C
 420  22 -6.500   -420            U=22  IMP:N,P=1 $Zr rod
 421  21 -6.315   -421  420       U=22  IMP:N,P=1 $U-ZrH fuel
 422  25 -7.896   -422            U=22  IMP:N,P=1 $Lower magneform
 423   0          -423            U=22  IMP:N,P=1 $Upper gap
 424  25 -7.896   -424            U=22  IMP:N,P=1 $Upper magneform
 425  26 -2.48    -425            U=22  IMP:N,P=1 $B4C Poison
 426   0          -426            U=22  IMP:N,P=1 $Lower Void
 427  25 -7.896   -427            U=22  IMP:N,P=1 $Upper SS plug
 428   0          -428            U=22  IMP:N,P=1 $Upper void
 429   0          -429  421       U=22  IMP:N,P=1 $Fuel/Clad gap
 430  25 -7.896   -430  429  428  427  426  425
                   424  423  422  U=22  IMP:N,P=1 $SS Clad
 431  24 -1.00    -431            U=22  IMP:N,P=1 $Water
 432  24 -1.00    -432  431  430  U=22  IMP:N,P=1 $Water
C
C  FREC-II Water Rods
C
 433  24 -1.00    -409            U=23  IMP:N,P=1 $FREC-II Water
C
C       frec centered on hex corner at 67.828 cm -- Comment by EJP
C
```

```
 440  24 -1.0    ((-440 -2821)
                 (441:-442:443:-444:445:-446:-449:451)
                 (516:-447:453)
                 (517:-516:-447:453)
                 (518:520:-456:519)
                 (454:455:-456:519)
                 (523:2821:-524:449)):(900 -440 2821)
                                       IMP:N,P=1
C
C  FREC-II Core  (FILL = 50)
C
 441   0         -441  442 -443  444 -445  446  447 -448 -2821
                 (517:-516:-447:453)
                 (516:-447:453)
                 (457:-458:459:-460:461:-462:-447:448)
                 (454:455:-456:519)
                 (477:-478:479:480:-447:448)
                 (472:471:-493:-476:470:-447:448)
                 (474:-475:-468:-476:493:-447:448)
                 (493:472:-473:-474:-447:448)
                 (463:464:-483:-469:470:-447:448)
                 (466:-467:-468:-469:483:-447:448)
                 (483:464:-465:-466:-447:448)
                 #488
                    fill=50              IMP:N,P=1
C
C
C   LATTICE Definition for FREC-II Core (UNIVERSE = 50)
C
C     array offset in y direction by -3.612 cm + -67.828 cm -- Comment by EJP
C
 442  24 -1.0       -450         lat=2  u=50   IMP:N,P=1
                    trcl=(0 -71.440 0)
               fill -16:15 -16:14 0:0
     23 31r
     23 31r
     23 31r
     23 31r      $ back
     23 14r               20 6r  20  20 5r  20                 23 1r
     23 13r              20 3r   23 7r        20 3r            23 1r
     23 12r           20 4r     23 6r          20 4r           23 1r
     23 11r         20 3r 22 20 23 5r  20 22 20  20 2r         23 1r
     23 10r     20 2r  22  20 2r  23 4r  20 1r  20  22 20 2r    23 1r
     23 9r          20 7r        23 3r  20 1r  20   20 4r      23 1r
     23 8r      20 23 1r  20 6r 20  20 2r  20  20 2r 23 1r 20   23 1r
     23 7r        20 23 2r  20 2r 23 7r 20 2r 23 2r   20        23 1r
     23 6r       20  23 3r 20 1r 23 8r  20 1r 23 3r     20      23 1r
     23 5r      20   23 4r  20   23 9r  20    23 4r      20     23 1r
     23 4r     20    23 4r 20    23 10r 20    23 4r       20    23 1r
     23 3r    20     23 4r 20    23 11r 20    23 4r        20   23 1r
     23 2r   20      23 4r 20    23 12r 20    23 4r         20  23 1r
     23 1r  20       23 4r 20    23 13r 20    23 4r          20 23 1r
     23 1r   20      23 3r 20    23 14r 20    23 3r         20  23 2r
     23 1r    20     23 3r 20    23 13r 20    23 3r        20   23 3r
     23 1r     20    23 3r 20    23 12r 20    23 3r       20    23 4r
     23 1r      20   23 2r 20 1r 23 11r 20 1r 23 2r      20     23 5r
     23 1r       20  23 1r 20 2r 23 10r 20 20 1r 23 1r  20      23 6r
     23 1r        20 23 20 3r    23  9r 20 20 2r 23    20       23 7r
     23 1r         20 4r  21     23  8r     21   20   20 3r     23 8r
     23 1r          20 1r  21 3r 23  7r 21  21 21 21 20 1r      23 9r
     23 31r     $ front
     23 31r
     23 31r
     23 31r
     23 31r
C
C ******************************************************
C *                                                    *
C *       END OF UNIVERSE DEFINITIONS AND FREC FILL     *
C *                                                    *
C ******************************************************
C
C   Additional FREC-II Cells
C
C
C   Left void chamber
C
 450  0      -481 -482 483 487  447 -448 #455                 IMP:N,P=1
 451  0      -484  485 486 487 -483  447 -448 #456            IMP:N,P=1
 452  7 -2.704  -463 -464 483 469 -470 447 -448
               (481:482:-483:-487:-447:448)                   IMP:N,P=1
```

```
 453  7 -2.704  -466 467 468 469 -483 447 -448
                (484:-485:-486:-487:483:-447:448)            IMP:N,P=1
 454  7 -2.704  -483 -464 465 466 447 -448                   IMP:N,P=1
 455  7 -2.704  -488 447 -448                                IMP:N,P=1
 456  7 -2.704  -489 447 -448                                IMP:N,P=1
C
C   Right void chamber
C
 460  0     -491 -492 493 497  447 -448 #465                 IMP:N,P=1
 461  0     -494  495 486 497 -493  447 -448 #466            IMP:N,P=1
 462  7 -2.704  -472 -471 493 476 -470 447 -448
                (492:491:-497:-493:-447:448)                 IMP:N,P=1
 463  7 -2.704  -474 475 468 476 -493 447 -448
                (494:-495:-486:-497:493:-447:448)            IMP:N,P=1
 464  7 -2.704  -493 -472 473 474 447 -448                   IMP:N,P=1
 465  7 -2.704  -498 447 -448                                IMP:N,P=1
 466  7 -2.704  -499 447 -448                                IMP:N,P=1
C
C   Rear void chamber
C
 470  0         -501  502 -503 -504 447 -448 #475 #476       IMP:N,P=1
 471  7 -2.704  -477 478 -479 -480 447 -448
                (501:-502:503:504:-447:448)                  IMP:N,P=1
 475  7 -2.704  -505 447 -448                                IMP:N,P=1
 476  7 -2.704  -506 447 -448                                IMP:N,P=1
C
C  FREC-II Cavity
C
 480 702 -1.0245e-3 -516  447  -453               IMP:N,P=1 $mid/upper cav void
 481  7 -2.704  -517 516 447 -453                 IMP:N,P=1 $mid/upper cav wall
 482  7 -2.704  -457 458 -459 460 -461 462 447 -448
                (517:-447:448)                    IMP:N,P=1 $mid hex
 483 702 -1.0245e-3 -518 -520 456 -519            IMP:N,P=1 $lower cav void
 484  7 -2.704  -454 -455 456 -519
                (518:520:-456:519)                IMP:N,P=1 $lower cav wall
 485  7 -2.704  -454 -455 519 -447                IMP:N,P=1 $lower lid
C
C Top Grid Plate
C
 486  7 -2.704  -441  442 -443  444 -445  446
                 517 -2821 448 -451       IMP:N,P=1 $top plate
C
C Bottom Grid Plate
C
 487  7 -2.704  -441  442 -443  444 -445  446
                -2821 449 -447
                (454:455:-449:447)       IMP:N,P=1 $bottom plate
C
C  Cav hex to front of face interface
C
 488  7 -2.704   522 -521 -2821 459 447 -448  IMP:N,P=1
C
C  rest of bottom acrr grid plate
C
 489  7 -2.704   -523 -2821 524 -449      IMP:N,P=1
C
C
C   EXPERIMENTAL or SPECTRUM MODIFYING BUCKETS  (700's)
C
C  Pb-B4C Bucket  (700-706)
C  Weight of Bucket per L. Martin (8/21/2003) - 446 lbs
C  Weight of Model Bucket                    - 450.81
C  Density of B4C layer changed to 2.12 g/cc to make weight 446.19 lbs
C
C
C 700 702 -1.0245e-3  -700 -100 1616 1500     IMP:N,P=1 $Inside Bucket
C 701  7   -2.7040    -701  700 -100          IMP:N,P=1 $1/16" Al liner
C 702 700  -11.350    -702 701 7091 7092 -100 IMP:N,P=1 $1" Pb on bottom
C 703 701  -2.5300    -703  7091 7092         IMP:N,P=1 $Boral on bottom
C 707 702 -1.0245e-3  -707  702 -100          IMP:N,P=1 $Slop between Cannister and Pb
C 708  8   -2.1200    -708                    IMP:N,P=1 $B4C layer on the bottom
C
C 704  7   -2.7040    -704  703  707  708
C                           7091 7092 -100    IMP:N,P=1 $Al layer
C 705  8   -2.1200  -705  704      -100        IMP:N,P=1 $B4C layer
C 706  7   -2.7040 -706 705 7091 7092 -100    IMP:N,P=1 $Al exterior
C 7091  3   -7.8960 -7091 -100                IMP:N,P=1 $Dowel 1
C 7092  3   -7.8960 -7092 -100                IMP:N,P=1 $Dowel 2
C
C
C
```

```
C  Standard Aluminum Experiment Bucket (710-711)
C   Add -900 to 710 and 711 if using 24" Bucket
C
C 710 702 -1.0245e-3  -710  1500 1616        IMP:N,P=1 $Inside Bucket
C 711  7   -2.7040    -711  710               IMP:N,P=1 $Aluminum Bucket
C
C
C  Pb-Poly Bucket (720-725) -- Designated as LP-1
C
C 720  702 -1.0245e-3  -720                 IMP:N,P=1 $Bottom of Inside
C 721  7   -2.7000  -721  720  726          IMP:N,P=1 $1/16" Al Liner
C 722  700 -11.350  -722  721  724  726     IMP:N,P=1 $0.4" Pb Layer
C 723  704 -0.9450  -723  722  726          IMP:N,P=1 $0.8" HDPE
C 724  704 -0.9450  -724                    IMP:N,P=1 $HDPE fill-in
C 725  7   -2.7000  -725  721  723  726     IMP:N,P=1 $Al Container
C 726  702 -1.0245e-3  -726                 IMP:N,P=1 $Top of Inside
C
C
C
C  Boombox for NG testing (730-738)
C
C 730  765 -7.28    -730  736  737  738     IMP:N,P=1 $Lower Boom Box
C 731  765 -7.28    -731  733               IMP:N,P=1 $Upper part of clamping ring
C 732  765 -7.28    -732  733               IMP:N,P=1 $Lower part of clamping ring
C 733  702 -1.0245e-3  -733                 IMP:N,P=1 $"Void" in clamping ring
C 734  702 -1.0245e-3  -734 732             IMP:N,P=1 $"Void" at ring lip
C 735  765 -7.28    -735                    IMP:N,P=1 $Plug
C 736  702 -1.0245e-3  -736 735             IMP:N,P=1 $"Void" around the plug
C 737  702 -1.0245e-3  -737                 IMP:N,P=1 $Lower "void"
C 738  702 -1.0245e-3  -738                 IMP:N,P=1 $Lip "void"
C
C
C     EXPERIMENT PACKAGES (1000's)
C
C     EXTERNAL WORLD
C
C
C
900 0              900  440             IMP:N,P=0 $Outside world
C
C

C ***********************************************************************
C *                          SURFACE CARDS                              *
C ***********************************************************************
C
C    Fuel Elements
C
10  RCC  0.000  0.000  23.32  0.000  0.000  52.25  0.2413  $Void
11  RCC  0.000  0.000  23.32  0.000  0.000  52.25  1.6840  $Fuel
14  RCC  0.000  0.000  23.32  0.000  0.000  52.25 1.72025  $Void
15  RCC  0.000  0.000  23.32  0.000  0.000  52.25 1.77125  $Niobium
16  RCC  0.000  0.000  23.32  0.000  0.000  52.25 1.82225  $Void gap
17  RCC  0.000  0.000 21.415  0.000  0.000  1.905 1.48700  $Lower plug
18  RCC  0.000  0.000  75.57  0.000  0.000  1.905 1.48700  $Upper plug
19  RCC  0.000  0.000  16.32  0.000  0.000  7.000 1.82225  $Lower plug
20  RCC  0.000  0.000  75.57  0.000  0.000  5.000 1.82225  $Upper plug
21  RCC  0.000  0.000  16.32  0.000  0.000  98.89 1.87325  $
22  RCC  0.000  0.000  16.32  0.000  0.000  98.89 5.00000  $Water
C
C   Control Rods
C
25 3 RCC 0.000  0.000  78.11  0.000  0.000  52.25 1.46050  $B4C poison
26 3 RCC 0.000  0.000  78.11  0.000  0.000  98.89 1.50495  $Void cap
27 3 RCC 0.000  0.000  78.11  0.000  0.000  98.89 1.74625  $poison sleeve
28 3 RCC 0.000  0.000  75.57  0.000  0.000   2.54 1.74625  $Magnaform plug
29 3 RCC 0.000  0.000  75.57  0.000  0.000 101.43 5.00000  $Water
30 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 0.24130  $Void
31 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.68400  $Fuel
32 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.72025  $Void
33 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.77125  $Niobium
34 3 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.82225  $Void gap
35 3 RCC 0.000  0.000  20.78  0.000  0.000   2.54 1.82225  $BeO plug
36 3 RCC 0.000  0.000 -79.22  0.000  0.000 100.00 1.82225  $Void
37 3 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 1.87325  $SS304
38 3 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 5.00000  $Water
C
C    Safety Rods
C
39 4 RCC 0.000  0.000  78.11  0.000  0.000  52.25 0.57150  $B4C poison
40 4 RCC 0.000  0.000  78.11  0.000  0.000  98.89 0.83185  $Void cap
```

```
41 4 RCC 0.000  0.000  78.11  0.000  0.000  98.89 1.74625  $Poison sleeve
42 4 RCC 0.000  0.000  75.57  0.000  0.000   2.54 1.74625  $Magnaform plug
43 4 RCC 0.000  0.000  75.57  0.000  0.000 101.43 5.00000  $Water
44 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 0.24130  $Void
45 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.68400  $Fuel
46 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.72025  $Void
47 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.77125  $Niobium
48 4 RCC 0.000  0.000  23.32  0.000  0.000  52.25 1.82225  $Void gap
49 4 RCC 0.000  0.000  20.78  0.000  0.000   2.54 1.82225  $BeO plug
50 4 RCC 0.000  0.000 -79.22  0.000  0.000 100.00 1.82225  $Void
51 4 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 1.87325  $SS304
52 4 RCC 0.000  0.000 -79.22  0.000  0.000 154.79 5.00000  $Water
C
C    Transient Rods
C
53 5 RCC 0.000  0.0 -76.2762  0.000  0.0  73.1012 1.20000  $Void
54   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 1.27000  $Al tubing
55   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 1.49860  $Water
56   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 2.02438  $Al guidex
57   RCC 0.000  0.000 -79.22  0.000  0.000 200.00 5.00000  $Water
58 5 RCC 0.000  0.000 -3.175  0.000  0.000   3.174 1.20000
59 5 RCC 0.000  0.000 -0.001  0.000  0.000 76.201 0.88000  $Poison
60 5 RCC 0.000  0.000 -0.001  0.000  0.000 76.201 1.20000  $Inner sleeve
61 5 RCC 0.000  0.000  76.20  0.000  0.000 123.80 1.20000  $Void
62 5 RCC 0.000  0.000 -100.0  0.000  0.00 23.7238 1.20000  $End plug
C
C    Aluminum Rods
C
90  RCC  0.000  0.000  15.41  0.000  0.000  66.14 1.77125  $Void in Al rod
C
C    Central Cavity Surfaces
C
100 RCC  0.000  0.000  0.000  0.000  0.000  95.00 11.6450  $Void
101 RCC  0.000  0.000  0.000  0.000  0.000  95.00 12.2800
102 RCC  0.000  0.000  0.000  0.000  0.000  95.00 13.9700
C
C   Cavity Additions
C
110 RCC  0.000  0.000  0.000  0.000  0.000 13.885 11.4300  $32-in pedestal
111 RCC  0.000  0.000 8.4748  0.000  0.000 2.8702  8.2550  $32-in inset
112 RPP -0.9525 0.9525  -8.255  8.255  11.345  13.885      $Inset Notch
113 RCC  0.000  0.000 13.885  0.000  0.000  1.270 10.3188  $Bottom plate (8-in)
114 RCC  0.000  0.000 32.935  0.000  0.000  1.270 10.3188  $Top plate (8-in)
115 RCC  0.000  0.000 15.155  0.000  0.000  17.78  5.7150  $Center void (8-in)
116 RCC  0.000  0.000 15.155  0.000  0.000  17.78  6.3500  $Support tube (8-in)
C
C    Top and Bottom Grid Plates
C
200 RCC  0.000  0.000  80.55  0.000  0.000   2.54 53.3500  $Top plate
201 PY  -34.925                                            $Cutoff of top plate
202 RCC  0.000  0.000  11.33  0.000  0.000   5.08 47.0000  $Bottom plate
C
C    Window to Radiography Lab
C
210  1 RPP  38.100 39.370  -26.670 26.670  16.41 80.55     $Ni plate
211  1 RPP  38.100 39.370  -38.100 38.100  16.41 80.55     $Water
212  1 RPP  48.895 100.00  -26.670 26.670  16.41 80.55     $Void
213  1 RPP  39.370 100.00  -38.100 38.100  16.41 80.55     $Aluminum
C
C   Nickel Plate near FREC-II
C
C 220  RPP  -36.830 36.830  -36.195 -34.925  16.41 83.09     $Nickel Plate
C
C
C  FREC Interface Plate
 220  RPP  -20.000 20.000  -36.124  -35.667  16.41 80.55  $Interface Plate
 221  RPP  -75.000 75.000  -36.124  -35.667  16.41 80.55  $Water outside interface plate
C
C    Hexes for the lattice, inner and outer core, and core boundary
C
320  RHP  0.0 0.0 -132.0  0.0 0.0 400.0 2.0855 0.0 0.0    $Lattice element
300  1 RHP  0.0 0.0 16.41 0.0 0.0 64.14 42.7 0.0 0.0      $outer core bound
310  1 RHP  0.0 0.0 0.0   0.0 0.0 95.00 11.65 0. 0.0      $Inner liner of cavity
311  1 RHP  0.0 0.0 0.0   0.0 0.0 95.00 12.285 0. 0.      $Outer liner of cavity
C
C   Plane to separate ACRR from FREC
2821  PY  -36.124
3101  PY  -35.667
C
C
C
```

```
C  FREC-II Surfaces
C
C   Nominal fuel element
C
 400  RCC  0.000  0.000  30.700  0.000  0.000  38.100  0.3175  $Zr rod
 401  RCC  0.000  0.000  30.700  0.000  0.000  38.100  1.7790  $U-ZrH rod
 402  RCC  0.000  0.000  21.800  0.000  0.000   8.900  1.7790  $Lower graphite
 403  RCC  0.000  0.000  68.800  0.000  0.000   8.900  1.7790  $Upper graphite
 404  RCC  0.000  0.000  77.700  0.000  0.000   0.480  1.7790  $Upper gap
 405  RCC  0.000  0.000  21.800  0.000  0.000  56.380  1.8220  $Gap
 406  RCC  0.000  0.000  20.520  0.000  0.000   1.280  1.8220  $Lower SS plug
 407  RCC  0.000  0.000  78.180  0.000  0.000   1.270  1.8220  $Upper SS plug
 408  RCC  0.000  0.000  20.520  0.000  0.000  58.930  1.8730  $SS Clad
 409  RCC  0.000  0.000   1.000  0.000  0.000   93.00  5.0000  $Water-Frec
C
C   Raised fuel element
C
 410 41 RCC  0.000  0.000  30.700  0.000  0.000  38.100  0.3175  $Zr rod
 411 41 RCC  0.000  0.000  30.700  0.000  0.000  38.100  1.7790  $U-ZrH rod
 412 41 RCC  0.000  0.000  21.800  0.000  0.000   8.900  1.7790  $Lower graphite
 413 41 RCC  0.000  0.000  68.800  0.000  0.000   8.900  1.7790  $Upper graphite
 414 41 RCC  0.000  0.000  77.700  0.000  0.000   0.480  1.7790  $Upper gap
 415 41 RCC  0.000  0.000  21.800  0.000  0.000  56.380  1.8220  $Gap
 416 41 RCC  0.000  0.000  20.520  0.000  0.000   1.280  1.8220  $Lower SS plug
 417 41 RCC  0.000  0.000  78.180  0.000  0.000   1.270  1.8220  $Upper SS plug
 418 41 RCC  0.000  0.000  20.520  0.000  0.000  58.930  1.8730  $SS Clad
C
C  FREC-II Fuel Follower and Safety Rod
C
 420 60 RCC  0.000  0.000  31.650  0.000  0.000  36.200  0.3175  $Zr rod
 421 60 RCC  0.000  0.000  31.650  0.000  0.000  36.200  1.7790  $U-ZrH rod
 422 60 RCC  0.000  0.000  30.380  0.000  0.000   1.270  1.8220  $Lower magneform
 423 60 RCC  0.000  0.000  67.850  0.000  0.000   0.640  1.8220  $Upper gap
 424 60 RCC  0.000  0.000  68.490  0.000  0.000   1.270  1.8220  $Upper magneform
 425 60 RCC  0.000  0.000  69.760  0.000  0.000  38.100  1.8220  $B4C Poison
 426 60 RCC  0.000  0.000 -76.000  0.000  0.000 106.380  1.8220  $Lower Void
 427 60 RCC  0.000  0.000 107.860  0.000  0.000   1.590  1.8220  $Upper SS plug
 428 60 RCC  0.000  0.000 109.450  0.000  0.000  17.000  1.8220  $Upper void
 429 60 RCC  0.000  0.000  31.650  0.000  0.000  36.200  1.8220  $Fuel/clad gap
 430 60 RCC  0.000  0.000 -76.000  0.000  0.000 202.450  1.8730  $SS clad
 431 60 RCC  0.000  0.000 126.450  0.000  0.000 100.000  1.8730  $Water
 432 60 RCC  0.000  0.000 -76.000  0.000  0.000 302.450  5.0000  $water
C
C  FREC-II boundary
C
 440 RCC  0.000 -67.828  0.000  0.000  0.000  95.000  73.000   $water around
c
c      Outer HEX boundary of FREC-II
c
 441 42 px  51.74
 442 42 px -51.74
 443 42 p   1 1.7320508076 0  103.47
 444 42 p   1 1.7320508076 0 -99.87
 445 42 p  -1 1.7320508076 0  103.47
 446 42 p  -1 1.7320508076 0 -103.47
C
 447    pz  17.68          $ top of frec lower grid plate (0.5 in higer than ACRR)
C                         (distance between plates is 25.25 in)
 448    pz  81.815         $ bottom of frec upper grid plate
 449    pz  13.87          $ bottom of frec lower grid plate
 451    pz  84.355         $ top of frec upper grid plate
 452    21 cz  26.60       $ frec cavity outer radius
 453    pz  95             $ upper boundary of the reactor
 454    40 c/z  0  -3.058 18.73
 455    40 py  10.822
 456    pz  0
C
C     frec cavity liner (inner dia = 20 in, 0.5 in wall)
C
 457    21 px  26.67
 458    21 px -26.67
 459    21 p   1 1.7320508076 0  53.34
 460    21 p   1 1.7320508076 0 -53.34
 461    21 p  -1 1.7320508076 0  53.34
 462    21 p  -1 1.7320508076 0 -53.34
C
C      left void chamber
C         outer surfaces
C
 463    43 p  -1.7321  1 0   0
 464    43 p   1.7321  1 0  48.006
```

```
 465    43 p  -1.7321  1 0 -26.316
 466    43 p   1.7321  1 0  34.289
 467    43 p  -1.7321  1 0 -63.244
 468    40 py -26.873
 469    43 p   1.7321  1 0   0
 470    40 py  21.641
C
C      right void chamber
C        outer surfaces
C
 471    44 p   1.7321  1 0   0
 472    44 p  -1.7321  1 0  48.006
 473    44 p   1.7321  1 0 -26.316
 474    44 p  -1.7321  1 0  34.289
 475    44 p   1.7321  1 0 -63.244
 476    44 p  -1.7321  1 0   0
C
C      rear void chamber
C        outer surfaces
C
 477    40 py -27.443
 478    40 py -44.817
 479    40 p  1.7321  1 0 -15.171
 480    40 p -1.7321  1 0 -15.171
C
C      left void chamber
C        inner surfaces
C
 481    43 p  -1.7321  1 0  -3.810
 482    43 p   1.7321  1 0  44.196
 483    43 p  -1.7321  1 0 -22.506
 484    43 p   1.7321  1 0  30.479
 485    43 p  -1.7321  1 0 -59.434
 486    40 py -24.968
 487    43 p   1.7321  1 0   3.810
c
 488    40 c/z -39.621  14.448 2.223   $ al pin
 489    40 c/z -35.451 -21.671 2.223   $ al pin
c
C      right void chamber
c        inner surfaces
 491    44 p   1.7321  1 0  -3.810
 492    44 p  -1.7321  1 0  44.196
 493    44 p   1.7321  1 0 -22.506
 494    44 p  -1.7321  1 0  30.479
 495    44 p   1.7321  1 0 -59.434
c
 497    44 p  -1.7321  1 0   3.810
c
 498    40 c/z  39.621  14.448 2.223   $ al pin
 499    40 c/z  35.451 -21.671 2.223   $ al pin
C
C      rear void chamber
c        inner surfaces
C
 501    40 py -28.713
 502    40 py -43.547
 503    40 p  1.7321  1 0 -17.711
 504    40 p -1.7321  1 0 -17.711
C
 505    40 c/z   8.341 -39.731 2.223   $ al pin
 506    40 c/z  -8.341 -39.731 2.223   $ al pin
C
C     u-zrh fuel lattice (same pitch as ACRR)
C
 450  RHP  0.0 0.0 -132.0  0.0 0.0 400.0 2.0855 0.0 0.0    $Lattice element
C
C
 516   21 cz  25.40    $ frec cavity inner radius
 517   21 cz  26.60    $ frec cavity outer radius
C
 518   40 c/z  0  -3.058 17.46
c     lower cav lid bottom
 519   pz  15.14
c     lower cavity plane is 13.88 cm - 3.058 cm = 10.822
 520   40 py  9.552
C
C      frec cavity to acrr interface ways dovetail
 521   px  15.4
 522   px -15.4
C
```

```
C
 523   cz  47.00
 524   pz  11.33
C
C
C
C   Buckets  (700's)
C
C  Pb-B4C Bucket
C
 700 7 RCC  0.0 0.0 6.35     0.0 0.0 85.09    6.27380 $Void
 701 7 RCC  0.0 0.0 6.26872  0.0 0.0 85.17128 6.35508 $0.032" Al liner
 702 7 RCC  0.0 0.0 3.65125  0.0 0.0 87.78875 9.76630 $Pb layers
 703 7 RCC  0.0 0.0 3.01625  0.0 0.0  0.63500 9.17575 $Boral
 704 7 RCC  0.0 0.0 1.90500  0.0 0.0 89.53500 10.1600 $Al layer
 705 7 RCC  0.0 0.0 1.90500  0.0 0.0 89.53500 11.1125 $B4C
 706 7 RCC  0.0 0.0 0.00000  0.0 0.0 91.44000 11.4300 $Al layer
 707 7 RCC  0.0 0.0 3.65125  0.0 0.0 87.78875 9.84250
 708 7 RCC  0.0 0.0 1.90500  0.0 0.0  0.63500 7.62000 $B4C bottom
7091 7 RCC  0.0 -8.890 0.00  0.0 0.0 91.44000 0.31750 $Dowel 1
7092 7 RCC  0.0  8.890 0.00  0.0 0.0 91.44000 0.31750 $Dowel 2
C
C  14" Aluminum Bucket
C
 710 7 RCC  0.0 0.0 0.15875  0.0 0.0 35.40125 11.27125   $Void
 711 7 RCC  0.0 0.0 0.00000  0.0 0.0 35.56000 11.43000   $Al bucket
C
C USE these for a 24" Aluminum Bucket
C
C 710 7 RCC  0.0 0.0 0.15875  0.0 0.0 60.80125 11.27125   $Void
C 711 7 RCC  0.0 0.0 0.00000  0.0 0.0 60.96000 11.43000   $Al bucket
C
C  LP-1 Surfaces
C
 720 7 RCC  0.0 0.0 5.74675  0.0 0.0 62.18825  7.46125   $Inside
 721 7 RCC  0.0 0.0 5.58800  0.0 0.0 73.15200  7.62000   $Al liner
 722 7 RCC  0.0 0.0 3.55600  0.0 0.0 64.37900  8.63600   $Pb
 723 7 RCC  0.0 0.0 2.54000  0.0 0.0 65.39500 10.66800   $HDPE
 724 7 RCC  0.0 0.0 3.55600  0.0 0.0  1.01600  7.62000   $HDPE fill-in
 725 7 RCC  0.0 0.0 0.00000  0.0 0.0 78.74000 11.43000   $Al Container
 726 7 RCC  0.0 0.0 67.9350  0.0 0.0 10.80500  7.46125
C
C  Boom Box Surfaces
C
 730  7 RCC  0.0 0.0 0.0      0.0 0.0 65.786   9.8425
 731  7 RCC  0.0 0.0 65.913   0.0 0.0  3.048   9.8425
 732  7 RCC  0.0 0.0 65.786   0.0 0.0  0.127   8.1280
 733  7 RCC  0.0 0.0 65.786   0.0 0.0  3.175   5.0800
 734  7 RCC  0.0 0.0 65.786   0.0 0.0  0.127   9.8425
 735  7 RCC  0.0 0.0 59.436   0.0 0.0  6.350   6.6675
 736  7 RCC  0.0 0.0 59.436   0.0 0.0  6.350   6.7945
 737  7 RCC  0.0 0.0  2.540   0.0 0.0 54.864   7.9375
 738  7 RCC  0.0 0.0 57.404   0.0 0.0  2.032   5.0800
C
C
C
C  EXPERIMENT SURFACES
C
C
C    External Cutoff
C
900 RCC  0.000  0.000  0.000  0.000  0.000  95.00 72.0000
C
C
C

C ********************************************************************
C *                           DATA CARDS                             *
C ********************************************************************
MODE N
KCODE   5000 1 15 315 11000
KSRC   20 0 50  0 20 60  30 0 40  0 30 60
C *************************
C *     TRANSFORMATIONS    *
C *************************
C
C  TR1 rotates the hexes for the outer core bound and the cavity liner
C
*TR1   0 0 0 30 60 90 120 30 90
C
C  TR3-->Movement of control rods -0.001 (full up) to -55.001 (full down)
```

```
C
C   Measured Up DC with 32-in pedestal is -39.731               (03/03/2004)
C   Measured Down DC is -30.851                                 (03/03/2004)
C    -->Up DC position of 1527 Rod Units
C    -->Down DC position of 2415 Rod Units
C   Measured Up DC with 8-in + 32-in pedestal is -40.421        (03/01/2004)
C   Measured Down DC with 8-in + 32-in pedestal is -31.291      (03/01/2004)
C    -->Up DC position of 1428 Rod Units
C    -->Down DC position of 2371 Rod Units
C   Measured Up DC with Pb-B4C on 32-in pedestal is -22.951     (03/09/2004)
C   Measured Down DC with Pb-B4C on 32-in pedestal is -10.741   (03/09/2004)
C    -->Up DC position of 3205 Rod Units
C    -->Down DC position of 4426 Rod Units
C   Measured DC with LP-1 on 32-in pedestal is -31.941          (03/11/2004)
C   Measured Down DC with LP-1 on 32-in pedestal is -23.721     (03/11/2004)
C    -->Up DC position of 2306 Rod Units
C    -->Down DC position of 3128 Rod Units
C
*TR3   0 0 -55.001
C
C  TR4-->Movement of safety rods 0.001 (full up) to -54.999 (full down)
C
C    Measured worth of safety rods:  -$2.12                     (03/30/2004)
C
*TR4   0 0  0.001
C
C  TR5-->Movement of transient rods 0 (full down) to 90 (full up)
C
C    Measured worth of transient rods:  -$4.14                  (03/30/2004)
C
*TR5   0 0  90
C
C  TR6-->Moves experiment package from origin (0 0 0) to fuel centerline
C
*TR6   0  0  49.445
C
C  TR7-->Puts buckets on 8" (34.205) or 32" (13.885) pedestals
C   Use 32" pedestal for LP-1
C   Use 8" for Standard Al buckets
C
*TR7   0  0  13.885
C
c     rotation of x-axis by 30 degrees and offset frec cavity by +1.422 in
c     = 3.612 cm + -67.828 cm = -64.216 cm
c
*TR21   0 -64.216 0 30 60 90 120 30 90
c
c     centerline of central cavity to centerline of frec hex
C
*TR40   0 -67.828 0
c
C     higher u-zrh elements
*TR41   0 0 1.892
c
c     rotation of x-axis by 30 degrees and offset frec -67.828 cm
c
*TR42   0 -67.828 0 30 60 90 120 30 90
C
c     centerline of central cavity to centerline of frec hex to left
c      *tr43   -53.696 -67.828 0
C
*TR43   -53.5 -67.828 0
C
C
C     centerline of central cavity to centerline of frec hex to right
*TR44    53.5 -67.828 0
C
C     movement of FRECII safety rods 0.001 (full up) to -39.053 (full down)
C     assume stroke is centerline of fuel follower to centerline of poison
C     *tr6   0 0  -39.053
*TR60  0 0  0.001
C
C *******************
C *  MATERIAL CARDS  *
C *******************
C  Materials cards use the latest available cross sections
C
C  UO2-BeO fuel (3.3447 g/cc)  (XSEC Temp - 293.6 K)
C   This density results in a fuel material per element of 1524.99 grams.
C   The value in the ACRR SAR for the fuel material per element is 1525 grams.
C
```

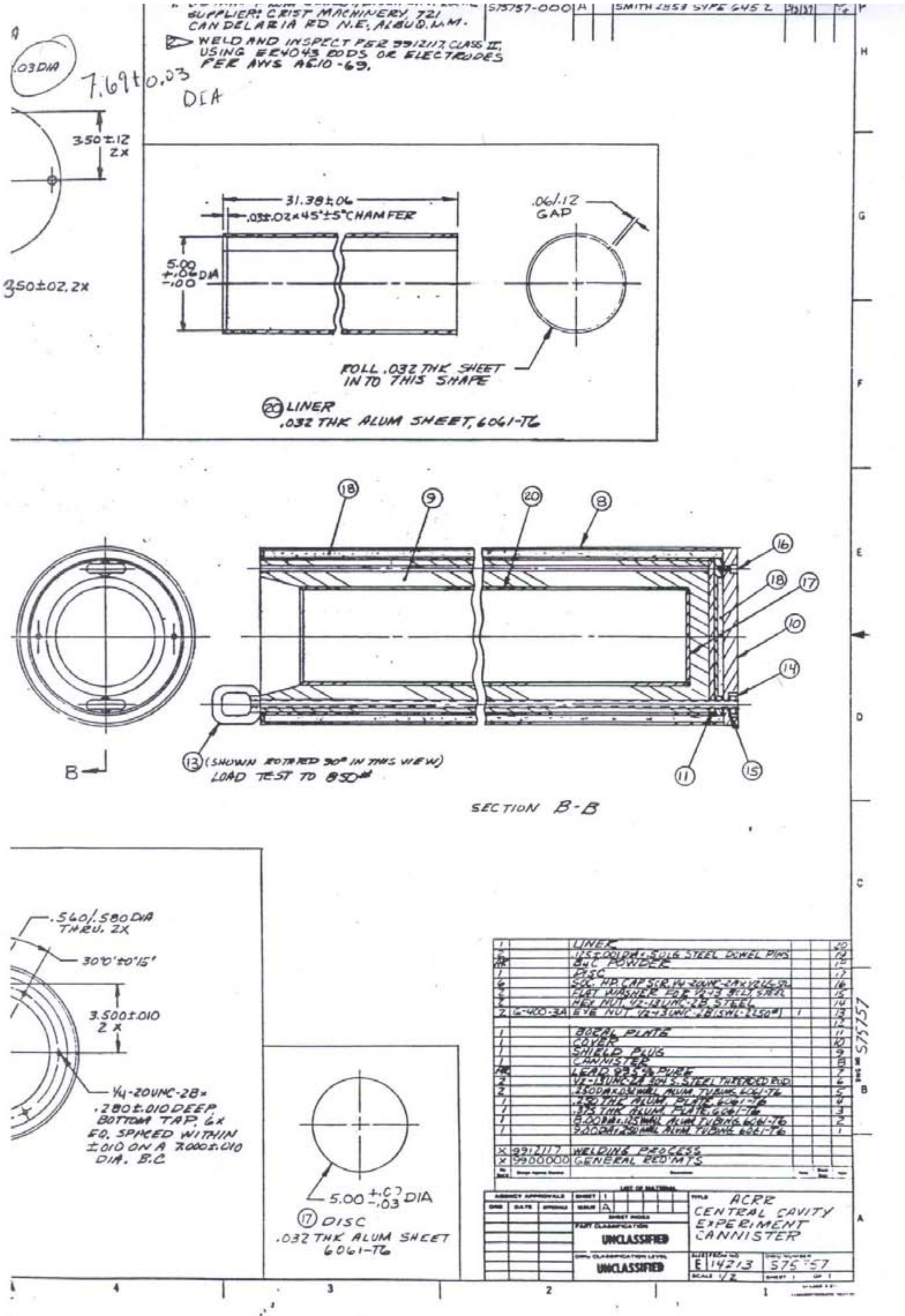
```
C
M1      4009.62c -0.2827602   8016.62c -0.5275554   8017.66c -0.0002136
       92235.66c -0.0662957  92238.66c -0.1222844  92234.66c -0.0004547
       92236.66c -0.0004358
MT1     beo.60t      $ S(alpha, beta) for BeO (Temp - 294 K)
C
C
C  UO2-BeO fuel (3.0102 g/cc)  -- This is the 90% fuel
C                                 (XSEC Temp - 293.6 K)
C   Included as a separate material to avoid warning message
C
C
M11     4009.62c -0.2827602   8016.62c -0.5275554   8017.66c -0.0002136
       92235.66c -0.0662957  92238.66c -0.1222844  92234.66c -0.0004547
       92236.66c -0.0004358
MT11    beo.60t      $ S(alpha, beta) for BeO (Temp - 294 K)
C
C     NIOBIUM (8.57 g/cc)
C
M2     41093.66c  1.0000
C
C
C  SS-304L from Ktech Materials Database Rev. 118
C   Material Number:  3410
C     Values are weight %
C      Si: 0.0100  Cr: 0.1900  Mn: 0.0200  Fe: 0.6800  Ni: 0.1000
C
C FM multiplier (neutrons):  1.76109641E-10  3410  -4   1
C FM multiplier (photons):   1.76109641E-10  3410  -5  -6
C
C  Density:  7.896 g/cc
C
M3     14028.62c -0.009187  14029.62c -0.000483  14030.62c -0.000329
       24050.62c -0.007930  24052.62c -0.159029  24053.62c -0.018380
       24054.62c -0.004661  25055.62c -0.020000  26054.62c -0.038390
       26056.62c -0.624930  26057.62c -0.014691  26058.62c -0.001989
       28058.62c -0.067198  28060.62c -0.026776  28061.62c -0.001183
       28062.62c -0.003834  28064.62c -0.001009
C
C
C     BeO (2.8 g/cc)
C
M4      4009.62c  0.5000     8016.62c  0.4998096    8017.66c  0.0001904
MT4     beo.60t      $ S(alpha, beta) for BeO (Temp - 294 K)
C
C     Water (1 g/cc)
C
M5    1001.62c  0.6665667    1002.66c  0.000100
      8016.62c  0.3332063    8017.66c  0.000127
MT5     lwtr.60t     $ S(alpha, beta) for water (Temp - 294 K)
C
C
C  Ni reflector
C           Values are weight %
C           Ni-58: 67.19780  Ni-60: 26.77586  Ni-61:  1.18346
C           Ni-62:  3.83429  Ni-64:  1.00859
C    Converted Data from Nuclear Wallet Card to w/o with "Weight_Frac" program
C  Density:  8.9020 g/cc
C
C
M6    28058.62c -0.6719780 28060.62c -0.2677586 28061.62c -0.0118346
      28062.62c -0.0383429 28064.62c -0.0100859
C
C
C  Al-6061 from Ktech Materials Database Rev. 118
C    Material Number:  3110
C     Values are weight %
C      Mg: 0.0110  Al: 0.9670  Si: 0.0080  Ti: 0.0007
C      Cr: 0.0020  Mn: 0.0013  Fe: 0.0056  Ni: 0.0004
C      Cu: 0.0030  Zn: 0.0010
C
C FM multiplier (neutrons):  3.55249469E-10  3110  -4   1
C FM multiplier (photons):   3.55249469E-10  3110  -5  -6
C
C  Density:  2.704 g/cc
C
M7     12000.62c -0.011000  13027.62c -0.967000  14028.62c -0.007350
       14029.62c -0.000387  14030.62c -0.000263  22000.62c -0.000700
       24050.62c -0.000084  24052.62c -0.001674  24053.62c -0.000193
       24054.62c -0.000049  25055.62c -0.001300  26054.62c -0.000316
       26056.62c -0.005147  26057.62c -0.000121  26058.62c -0.000016
```

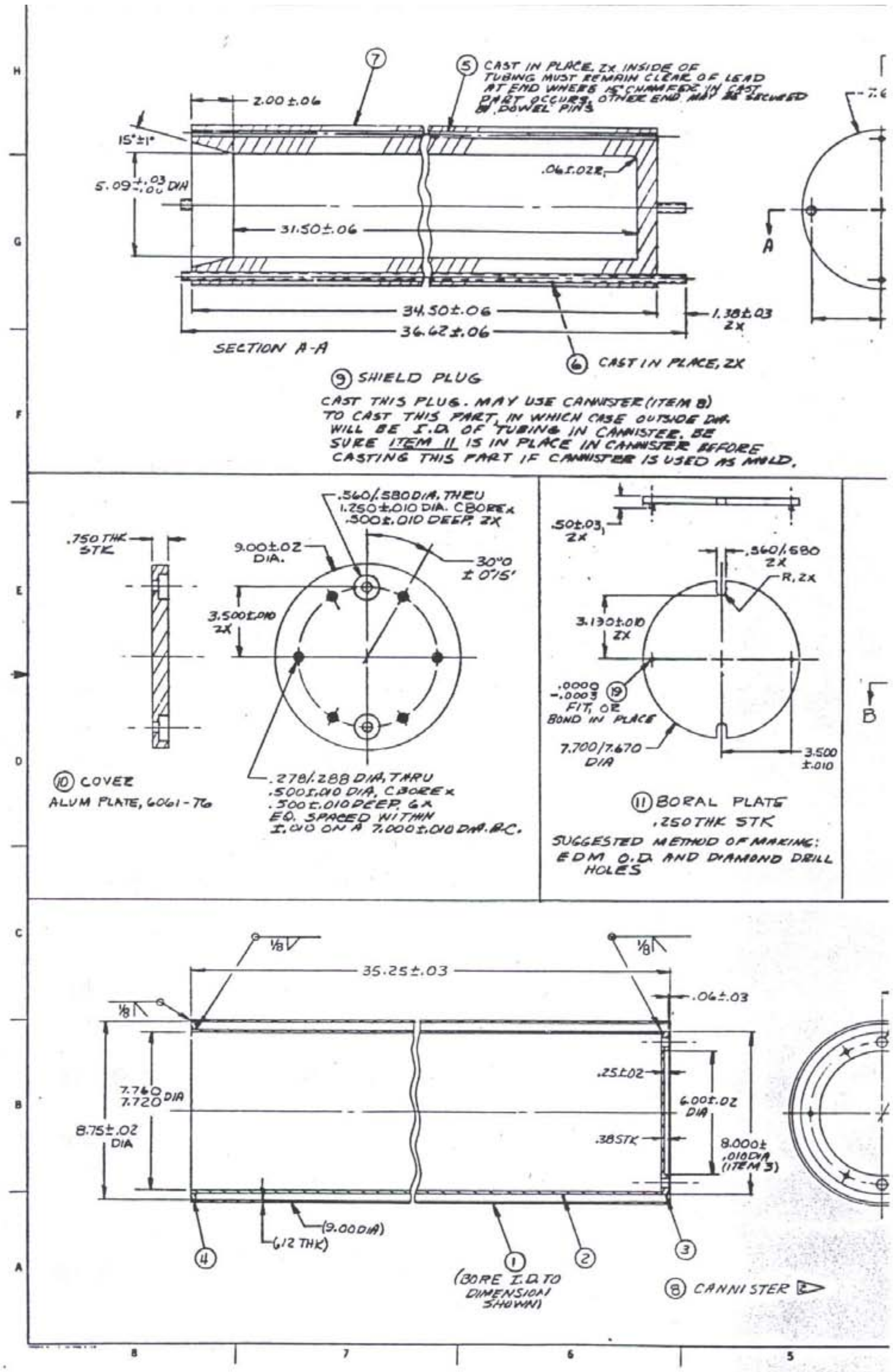
```
       28058.62c -0.000269  28060.62c -0.000107  28061.62c -0.000005
       28062.62c -0.000015  28064.62c -0.000004  29063.62c -0.002055
       29065.62c -0.000945  30000.42c -0.001000
C
C
C    B4C poison (2.48 g/cc)
C
M8       6000.66c  0.20000   5010.66c  0.159200   5011.66c  0.640800
C
C
C
C     u-zrh fuel (12w/o, 20% enriched, H=1.625)
M21    40000.66c -0.86912     1001.62c -0.01560
       92235.66c -0.02306    92238.66c -0.09222
MT21  h/zr.60t   $ S(alpha, beta) for Zr-H (Temp - 294 K)
C
C     zr
C
M22   40000.66c -1.0
C
C     c (graphite)
C
M23   6000.66c -1.0
MT23  grph.60t    $ S(alpha, beta) for graphite (Temp - 294 K)
C
C     frec h2o
C
M24   1001.62c  0.6665667    1002.66c  0.000100
      8016.62c  0.3332063    8017.66c  0.000127
MT24  lwtr.60t  $ S(alpha, beta) for water (Temp - 294 K)
C
c
C
C    FREC SS-304L (7.896 g/cc)
C
M25    14028.62c -0.009187  14029.62c -0.000483  14030.62c -0.000329
       24050.62c -0.007930  24052.62c -0.159029  24053.62c -0.018380
       24054.62c -0.004661  25055.62c -0.020000  26054.62c -0.038390
       26056.62c -0.624930  26057.62c -0.014691  26058.62c -0.001989
       28058.62c -0.067198  28060.62c -0.026776  28061.62c -0.001183
       28062.62c -0.003834  28064.62c -0.001009
C
C
C    B4C poison (2.48 g/cc)
C
M26      6000.66c  0.20000   5010.66c  0.159200   5011.66c  0.640800
C
C
C  Natural Lead
C  True Weight %:  Pb-204:  1.37808  Pb-206: 23.95550
C                  Pb-207: 22.07430  Pb-208: 52.59212
C  Weight % based on Available MCNP XSEC:
C                  Pb-206: 24.29024  Pb-207: 22.38275
C                  Pb-208: 53.32701
C
C    Converted Data from Nuclear Wallet Card to w/o with "Weight_Frac" program
C  Density is 11.35 g/cc from Nuclear Wallet Cards.
C
C
M700  82206.66c -0.2429024  82207.66c -0.2238275
      82208.66c -0.5332701
C
C
C Boral Plate Composition
C
C  Composition found in Nuclear Science and Engineering
C   Vol. 65, No. 1, pgs. 41-48, January 1978.
C   Values are weight %
C         B: 27.40   C:  7.61  Al: 63.68
C        Cu:  0.09  Zn:  0.16  Fe:  0.45
C        Cr:  0.10  Mn:  0.10  Mg:  0.05
C        Ti:  0.10  Li:  0.26
C
C   Density:  2.53 g/cc
C
C
M701   5010.66c -0.050242   5011.66c -0.223758    6000.66c -0.076100
      13027.62c -0.636800  29063.62c -0.000616  29065.62c -0.000284
      30000.42c -0.001600  26056.62c -0.004500  24050.62c -0.000042
      24052.62c -0.000837  24053.62c -0.000097  24054.62c -0.000024
      25055.62c -0.001000  12000.62c -0.000500  22000.62c -0.001000
```

```
       3006.66c -0.000171   3007.66c -0.002429
C
C
C
C  Air
C   Standard Density:  1.205e-3 g/cc @ 20 deg C, 1 atm
C   Albuquerque:       1.0245e-3 g/cc in ABQ
C  See Attix p.531-532
C
M702   7014.62c -0.752308   7015.66c -0.002960   8016.62c -0.231687
       8017.66c -0.000094   6000.66c -0.000124  18000.42c -0.012827
C
C
C
C   HELIUM  For Leak Test
C    @ 2 atm density = 3.57e-4 g/cc
C
M703   2003.66c 0.00000137  2004.62c  0.99999863
C
C HDPE-> (C2H4)n     --          --
C                    |   H    H   |
C                    |   |    |   |
C                   -|-  C -- C  -|-
C                    |   |    |   |
C                    |   H    H   |
C                    --          --
C
M704   1001.60c  0.666667   6000.60c  0.333333
MT704  poly.01t
C
C
C   A517 Carbon Steel  (den = 7.28 g/cc)
C     Modified to match the mill test cert.
C     from Tubos de Acero de Mexico, S.A.
C
C   Summary of MatMCNP Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C   C-12       0.0118115          0.0025688         0.0009385
C   C-13       0.0001326          0.0000312         0.0000105
C  Si-28       0.0048924          0.0024807         0.0003887
C  Si-29       0.0002484          0.0001305         0.0000197
C  Si-30       0.0001638          0.0000890         0.0000130
C  Cr-50       0.0000184          0.0000167         0.0000015
C  Cr-52       0.0003557          0.0003348         0.0000283
C  Cr-53       0.0000403          0.0000387         0.0000032
C  Cr-54       0.0000100          0.0000098         0.0000008
C  Mn-55       0.0078340          0.0078003         0.0006225
C  Fe-54       0.0568920          0.0556172         0.0045205
C  Fe-56       0.8930822          0.9053674         0.0709617
C  Fe-57       0.0206252          0.0212829         0.0016388
C  Fe-58       0.0027448          0.0028820         0.0002181
C  Cu-63       0.0007628          0.0008700         0.0000606
C  Cu-65       0.0003400          0.0004001         0.0000270
C  Mo-92       0.0000068          0.0000114         0.0000005
C  Mo-94       0.0000043          0.0000072         0.0000003
C  Mo-95       0.0000073          0.0000126         0.0000006
C  Mo-96       0.0000077          0.0000133         0.0000006
C  Mo-97       0.0000044          0.0000077         0.0000003
C  Mo-98       0.0000111          0.0000197         0.0000009
C  Mo-100      0.0000044          0.0000080         0.0000004
C
C  The total compound atom density (atom/b-cm):  0.07945702
C
M765    06000.66c  0.0119440  14028.62c  0.0048924  14029.62c  0.0002484
        14030.62c  0.0001638  24050.62c  0.0000184  24052.62c  0.0003557
        24053.62c  0.0000403  24054.62c  0.0000100  25055.62c  0.0078340
        26054.62c  0.0568920  26056.62c  0.8930822  26057.62c  0.0206252
        26058.62c  0.0027448  29063.62c  0.0007628  29065.62c  0.0003400
        42000.66c  0.0000460
C
C *******************
C *    TALLIES      *
C *******************
C
C
PRINT  10 60 100
```

APPENDIX C – EXPERIMENT PLAN EXTRACTS

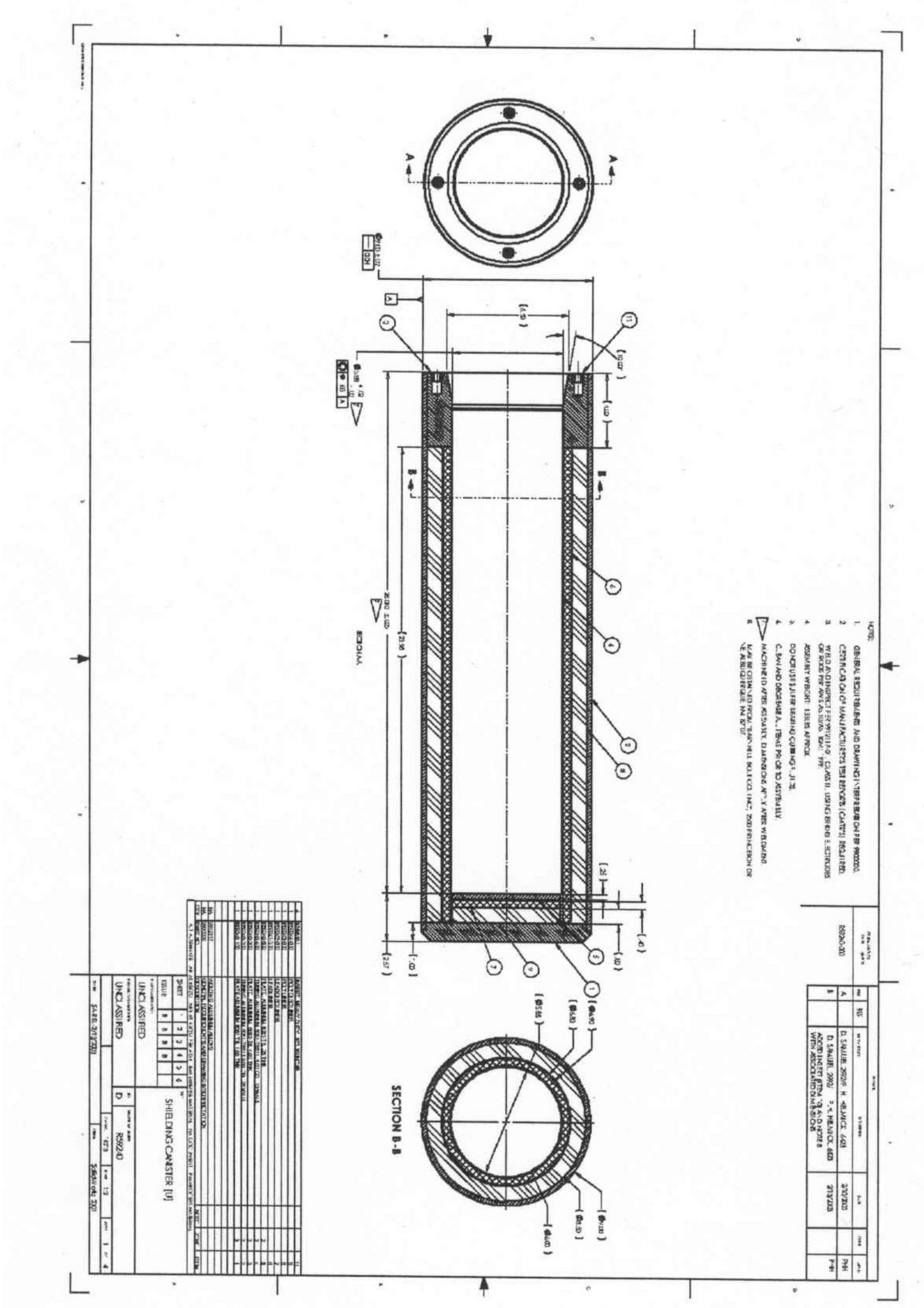
Pb-B4C Bucket Drawings



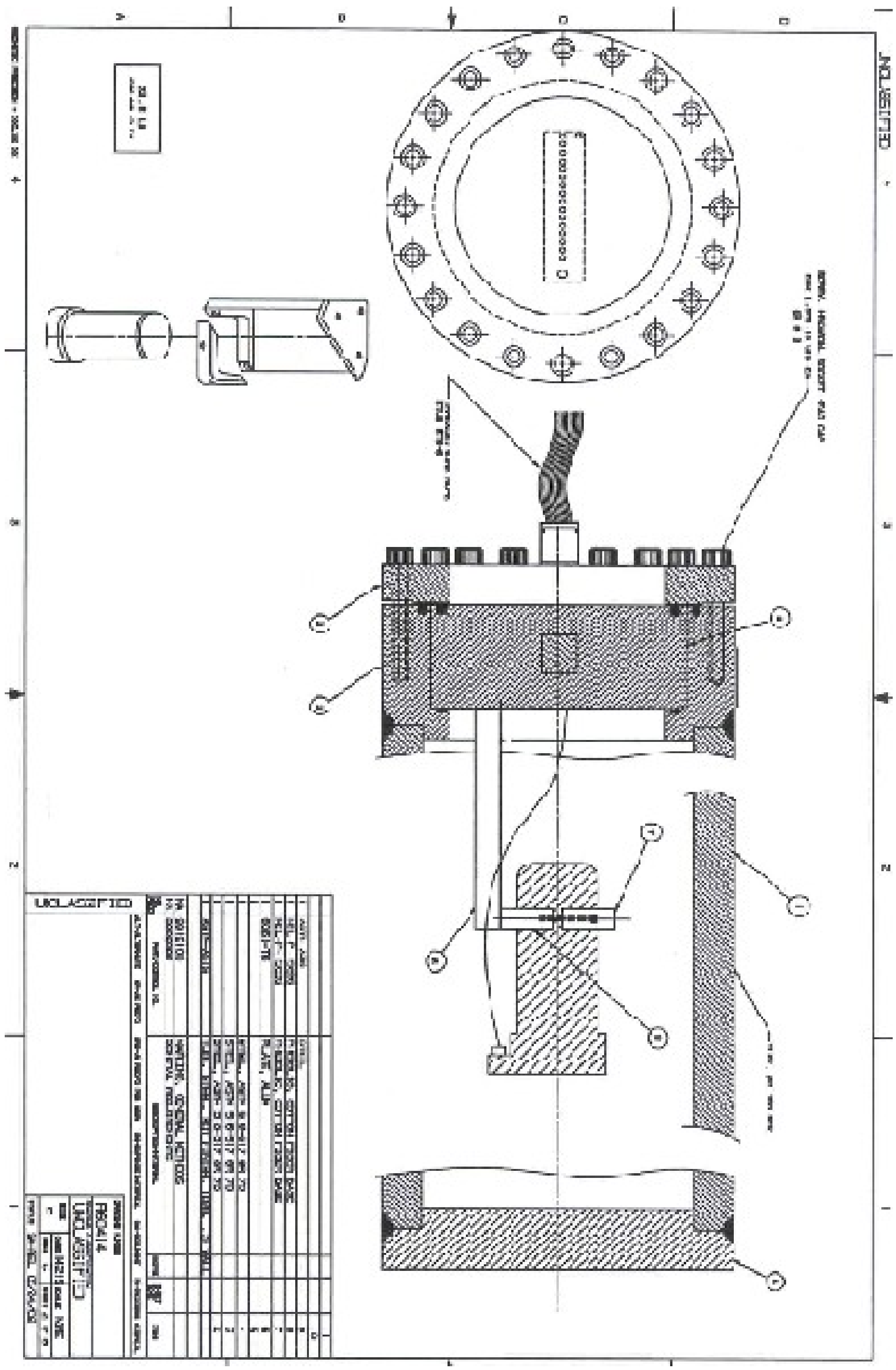


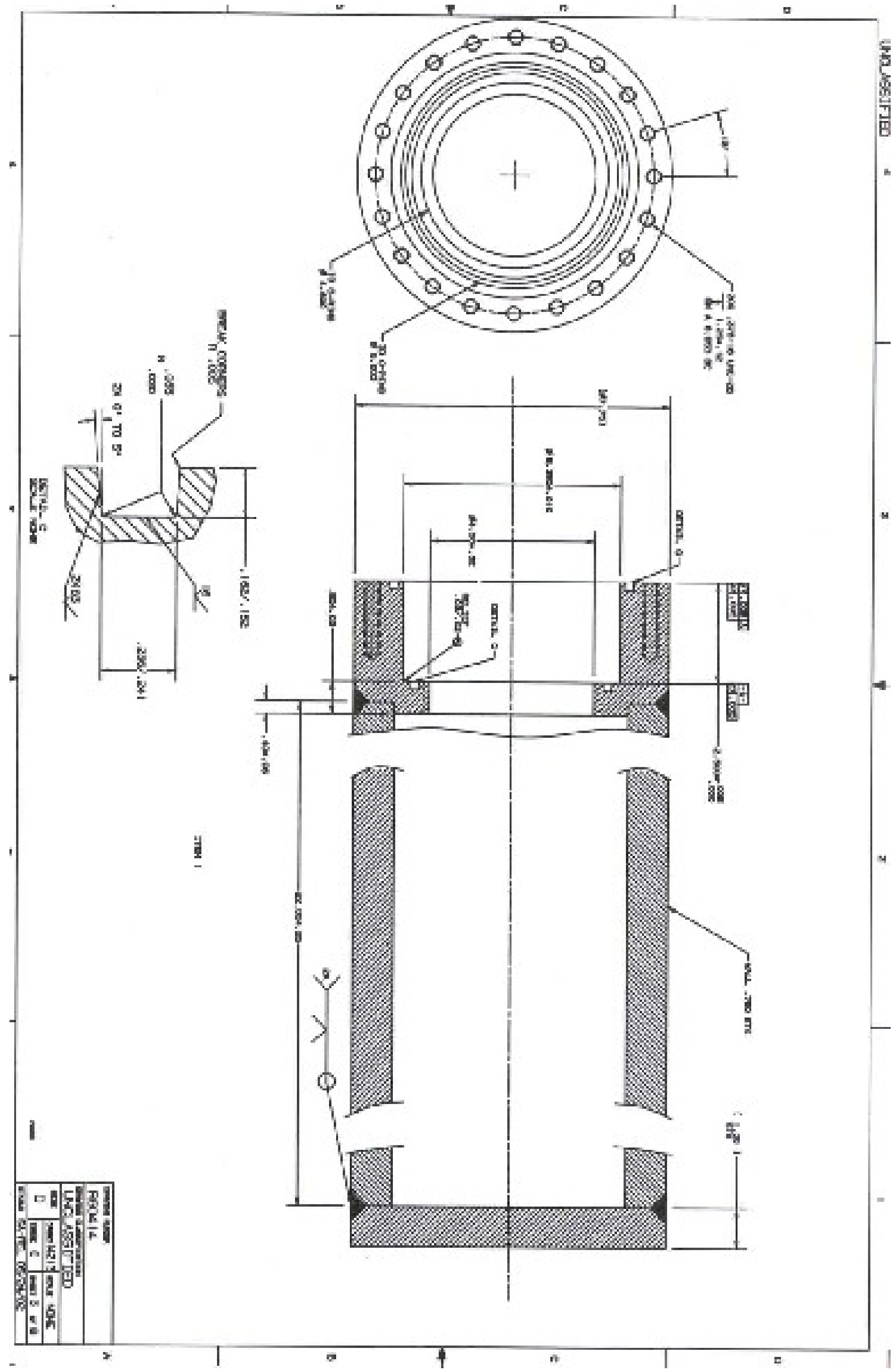
SECTION A-A
9 SHIELD PLUG
CAST THIS PLUG. MAY USE CANNISTER (ITEM 8) TO CAST THIS PART, IN WHICH CASE OUTSIDE DIA. WILL BE I.D. OF TUBING IN CANNISTER. BE SURE ITEM 11 IS IN PLACE IN CANNISTER BEFORE CASTING THIS PART IF CANNISTER IS USED AS MOLD.
5 CAST IN PLACE, 2X INSIDE OF TUBING MUST REMAIN CLEAR OF LEAD AT END WHERE IS CHAMFER IN CAST PART OCCURS. OTHER END MAY BE SECURED BY DOWEL PINS
6 CAST IN PLACE, 2X
10 COVER
ALUM PLATE, 6061-T6
11 BORAL PLATE
.250 THK STK
SUGGESTED METHOD OF MAKING: EDM O.D. AND DIAMOND DRILL HOLES
8 CANNISTER
(BORE I.D. TO DIMENSION SHOWN)

LP-1 Drawing



Boom Box Drawings

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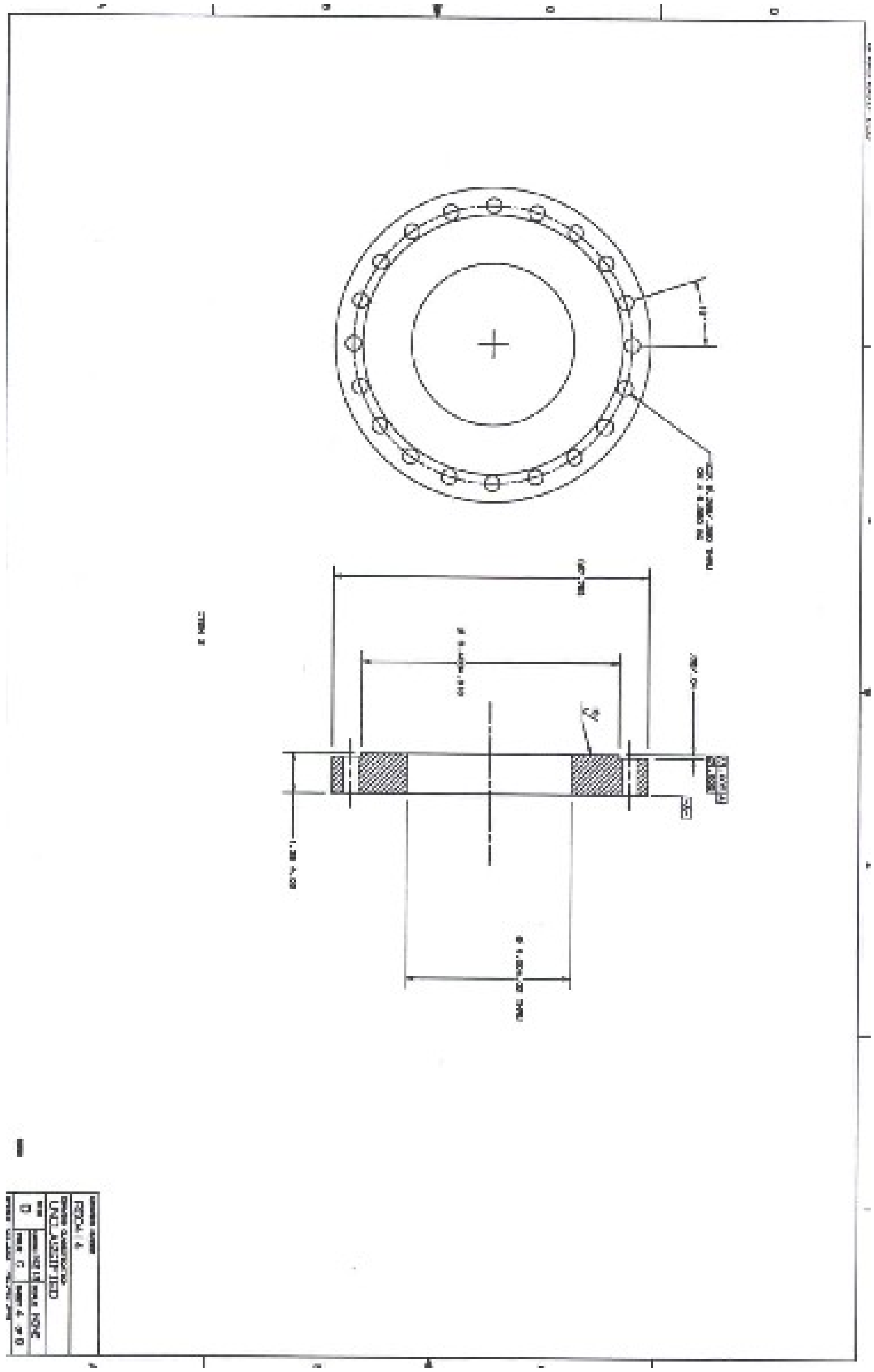

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